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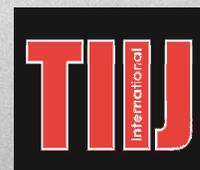
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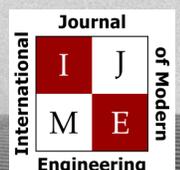
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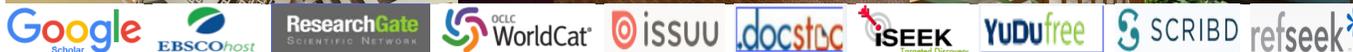
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# REMOBOT: A SYSTEM FOR TELEOPERATING AN INDUSTRIAL COLLABORATIVE ROBOT FOR SPACE REPAIR USING VIRTUAL REALITY

Haoyu Wang, Central Connecticut State University; Ryan Mecham, Central Connecticut State University;  
Biao Zhang, ABB US Corporate Research

## Abstract

The goal of this research study was to develop a technology to teleoperate an industrial collaborative robot to conduct maintenance or repair jobs by itself or collaborate with a human in space. To this end, the authors developed ReMoBot, a system that controls an ABB Yumi collaborative robot (IRB14000) through a virtual reality (VR) device, HTC Vive. The system allows a user to control the robot's motion simply by moving his/her arms. The system was tested at ABB using the programming and simulation software RoboStudio, and also on a real Yumi robot. Input motion data from Vive controllers and output motion data from Yumi were collected and analyzed to illustrate the effectiveness of the system.

## Introduction

One of the major challenges to exploring deep space is the sustainability of the crafts we send to space. NASA's most recent rover, Curiosity, landed on Mars in 2012 and has been successfully exploring the Martian surface ever since. The \$2.5 billion price tag and the eight-month travel time make us think about what we can do to lengthen the rover's life as much as possible. As a machine, a rover needs maintenance or repair just like our cars. So while we cannot yet send humans to Mars, the only option is to send a mobile robot to do the job. However, for maintenance or repair (MR) jobs, humans are much better than robots in judging the situation, coming up with strategies and tactics, and conducting complex actions. It would be nice to have a human expert to operate the mobile robot to conduct MR jobs on another rover remotely. Obviously, this should be done when Mars is closest to Earth or a spacecraft carrying human experts to minimize the measurement or control signal latency. Eventually, a more reliable prediction model and related action planning are needed to make teleoperation of robots in deep space possible.

Currently, when astronauts repair objects in space, they need to do space walks with their thick and bulky space-suits, which prevent them from moving freely. In addition, they are challenged by limited oxygen and all of the risks without protection of the spacecraft. For complex repair

jobs, several astronauts need to work together. This dramatically increases the consumption of supplies and risks of having more than one astronaut exposed to space. It would be quite advantageous if the astronauts could operate the robots to do the repair jobs, while they themselves remained inside the spacecraft.

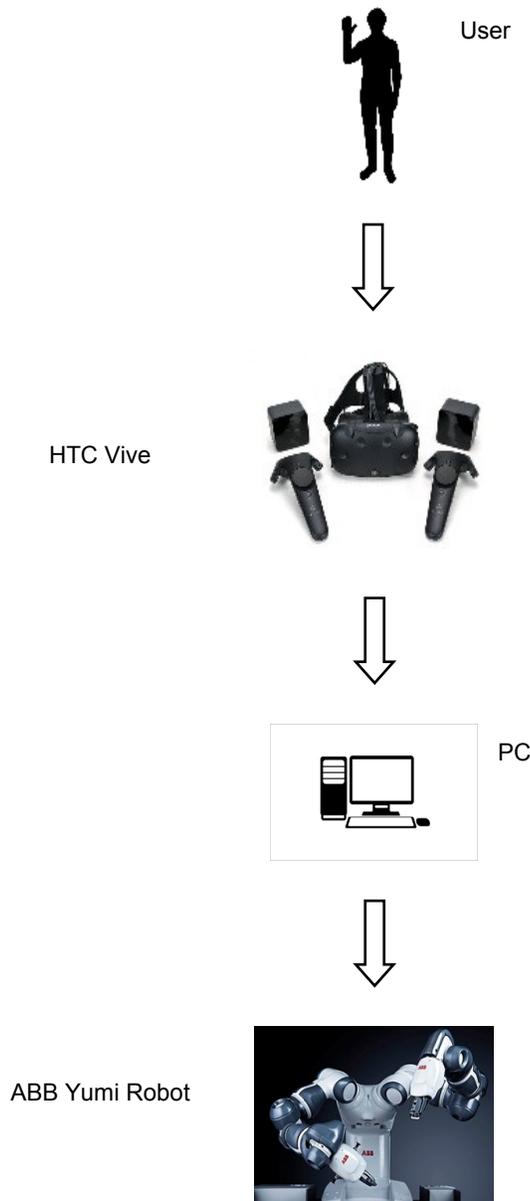
The key to the solution is robot teleoperation, or telerobotic application. The first systems date back to the 1940s, when humans handled radioactive material from behind shielded walls [1]. Since that time, many telerobotic applications have appeared. Some modern systems include the da Vinci system, made by Intuitive Surgical, Inc. [2], and tele-robot explosive ordnance disposal and observation robot PackBot, made by iRobot [3]. In orbital robotics, the German technology experiment ROKVISS (robot component verification on ISS) is the most advanced telerobotic system [4]. It resulted in the development of Robonauts, which can be remotely controlled from Earth to help real astronauts during extravehicular activities (EVAs) or to perform maintenance or repair work [5]. Artigas used a force-feedback joystick to control a robot in the space station [6]. To date, much work has been done on teleoperation schemes and modeling [7-12]. Collaborative teleoperation between multiple robots has also been reported in the literature [13-21]. Supervisory control with the master-slave model provided a way to balance autonomy and direct human control [22-25].

Different from the afore-mentioned applications, the targets for this current study was a space repair telerobotic solution using VR and collaborative robot integration [26]. Collaborative industrial robots are relatively cheap, sturdy, durable, and readily available in large quantities. Collaborative robots can also safely work around humans, which makes this solution very appealing. The novel idea here was to develop a teleoperated robot system using VR and an industrial collaborative robot (Cobot). The previous applications would have used either special robots, which have different motion control and communication methods, or industrial robots, which are not safe for humans to work with collaboratively. In this current study, the authors laid the foundation for combining VR with an industrial Cobot for both communications and motion control. The collaborative robot enables applications in which the human worker

and remote-controlled robot work together on tasks on the spacecraft. The customization of industrial robots to qualify them for the conditions of space is left for future studies.

## Methodology: The ReMoBot System

Figure 1 shows the structure of the ReMoBot system, which includes a VR device, a PC, and an industrial robot. The computer reads the position and orientation data from the VR device then processes the data and sends commands to the robot.



**Figure 1. The ReMoBot System Diagram**

The HTC Vive VR set was chosen due to its exceptional performance in motion tracking and user-friendly programming interface. It comes with two wireless infrared Lighthouse cameras, which are placed in the corners of a room, and follows the sensors on either the headset or a controller. It allows the user to move freely within a regular-size room and will track user movements. The ABB Yumi robot was chosen for the project because it is the dual-arm collaborative robot that has the highest safety and accuracy as well as an outstanding offline programming software and simulator. To control the robot, the user holds a Vive controller in each hand. Vive uses Lighthouse technology to accurately track the motion of the headset or controllers. While the user's hands are moving, data of the controller's position and orientation is acquired by software developed by the authors. The software processes the data in order to create a target to move the arms of virtual Yumi robot in RoboStudio, or the real Yumi robot. RoboStudio is offline programming and simulation software from ABB.

## ReMoBot Software Development

The software has two components. The first was developed by the authors using C# language in Microsoft Visual Studio 2015 to acquire motion data through the Vive application programming interface (API). Motion data are used to determine appropriate target points, which are then sent to Yumi. The other component of the software was written in RAPID language in RoboStudio to control the actual motion of the Yumi robot. Figure 2 shows a flowchart of information flow in the software.

## Experimental Analysis

Figure 3 shows how the ReMoBot system was first connected to the virtual Yumi in a RoboStudio simulation for programming, debugging, and visual testing. After that, it was connected to a real Yumi robot for performance testing. Figure 4 shows how the two Vive bases were set up on tripods in diagonal corners of a 20'x12' conference room. Chairs and tables in the conference room simulated obstacles in a real-world working environment. Three experiments were conducted to test the performance of the ReMoBot system. The ReMoBot software can monitor and record position and orientation (in the form of quaternions) of the Vive controller in a data log file. Another program was written in RAPID language and ran in the background so that the Yumi robot controller could monitor and record the actual position and orientation of the Yumi robot into a data log file. The analysis of the data files was done in MATLAB to show the consistency between the input from user through a Vive controller and the output from the Yumi robot.

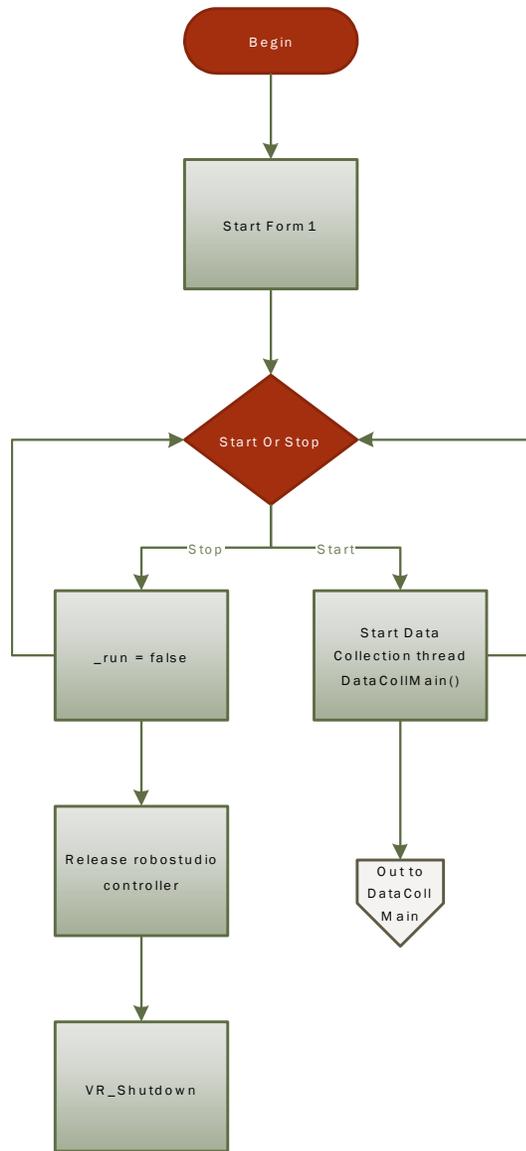


Figure 2. ReMoBot Software Flowchart



Figure 3. ReMoBot Simulation in RoboStudio

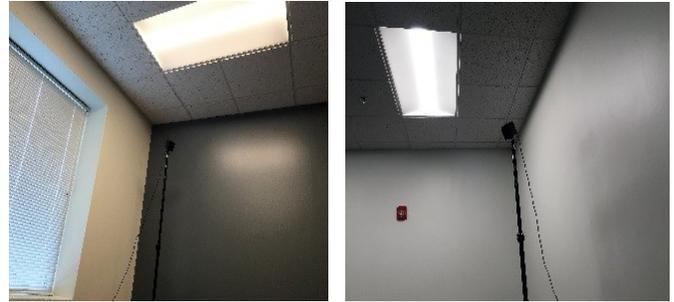


Figure 4. Vive Bases Setup

## Experiment 1: Draw a Line on Paper

In this experiment, a user held a controller in his left hand to control the left arm of the Yumi robot and draw a line on a piece of paper; there was a marker attached to the end gripper of Yumi's left arm. Figure 5 shows the setup and the line left on the paper. It is obvious that there is discontinuity in the line. This was due mostly to the fact that it is hard for human to have a steady hand in any of the X, Y, and Z directions. Force or torque feedback from Yumi will be used to improve contact between the marker and the paper in the future. The chart at the top of Figure 6 was drawn based on the raw motion data from the Vive controller. ReMoBot software transformed the raw data to reference the motion target data for the Yumi robot. The Vive controller uses units of meters, which are transformed to millimeter for the Yumi robot. Yumi's work range is 0.5 meters. The range of motion of an adult is easily more than that, so a scale factor needed to be applied to avoid being out of Yumi's reach.



Figure 5. Experiment Marker Setup and Line Drawn

The last step was to transform the motion from Vive's coordinate system to Yumi's coordinate system. In Figure 6, the chart on top illustrates motion data before transformation. The chart at the bottom was generated with actual motion data from Yumi. Figure 7 shows the tracking error, which was calculated as the Euclidian distance between TCP positions recorded on Yumi and the user's hand position read from Vive. It can be seen that Yumi accurately followed the movement of the Vive controller.

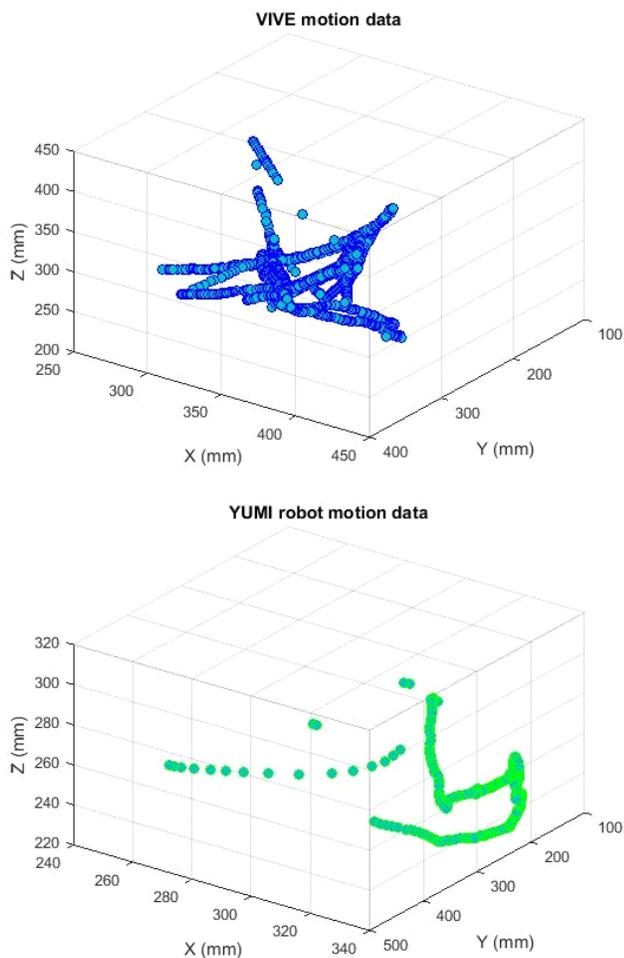


Figure 6. Experiment 1 Motion Data of Vive and Yumi

## Experiment 2: Smoothing Yumi Robot Motion

Though Yumi accurately followed the Vive controller, it did not, at times, move smoothly. The reason was that the ReMoBot sent a new target to Yumi in very small increments based on Vive's resolution. Thus, Yumi was accelerating and decelerating most of the time, which resulted in

bumpy movements, especially when changing directions. In this experiment, a smoothing technique was applied such that the ReMoBot software would only send a new target to Yumi when the movement was bigger than one millimeter. Figure 8 shows the smoothed robot position calculated by Vive (top) and the actual Yumi motion with the smoothed input (bottom). It shows much better correlation between Vive and Yumi. Figure 9 shows the tracking error.

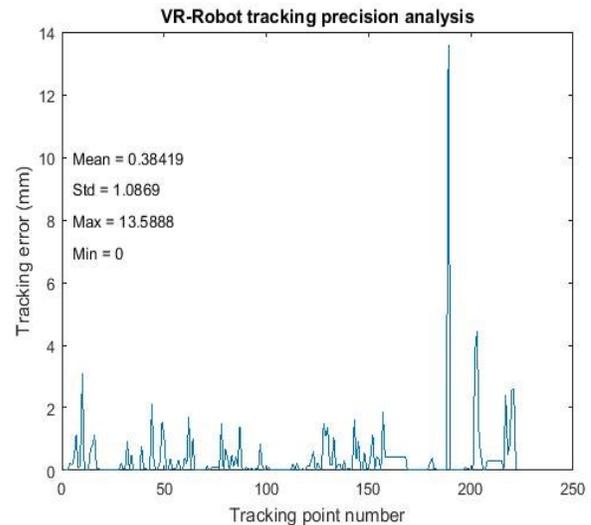


Figure 7. Experiment 1 Tracking Error

## Experiment 3: Drawing a Cross Sign

This third experiment was based on experiment 2. The goal was to ask the user draw a “+” sign on paper after smoothing. This was a more challenging job, due to motion direction changes and longer times required to keep contact with the paper. Figure 10 shows that Yumi was able to successfully trace Vive to complete the job. Figure 11 shows the related tracking error. The mean and standard deviation of the tracking error are slightly higher than were the cases for experiments 1 and 2. The result was expected, because the user's hand would be more unstable when drawing the perpendicular lines of the plus sign.

## Conclusions

In this study, a ReMoBot was developed to allow control of a collaborative robot, a Yumi robot from ABB, through a VR device, HTC Vive. Experiments showed that it can control Yumi with good resolution of motion, especially after smoothing the targets. This initial study laid the foundation for human-robot collaboration with virtual reality and augmented reality technology. Future research work will include:

- Apply different filters and control laws to optimize the robot's motion.
- Handle the communication latency for deep space, such as Mars.
- Automatically map the human motion to robot task motion space.
- Customize the scaling between the Vive controller's movements to the robot's motion in order to fit different persons for ergonomics.
- Apply the process to other robots that have different kinematic and dynamic models.
- Record the robot's motions controlled by a human operator through the HTC Vive controller then replay/repeat the motion.
- Apply the system to remote repairing tests and other human-robot collaboration applications.

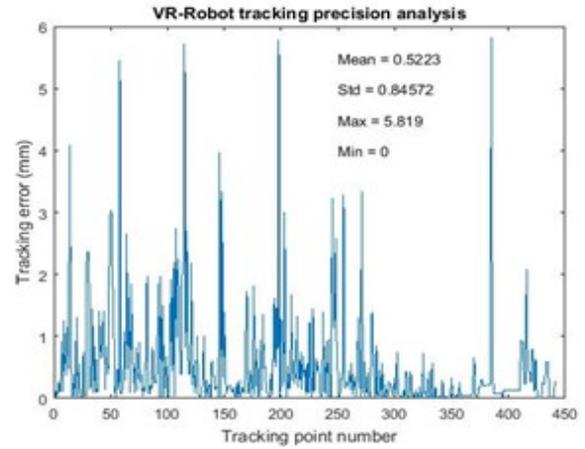


Figure 9. Experiment 2 Tracking Error

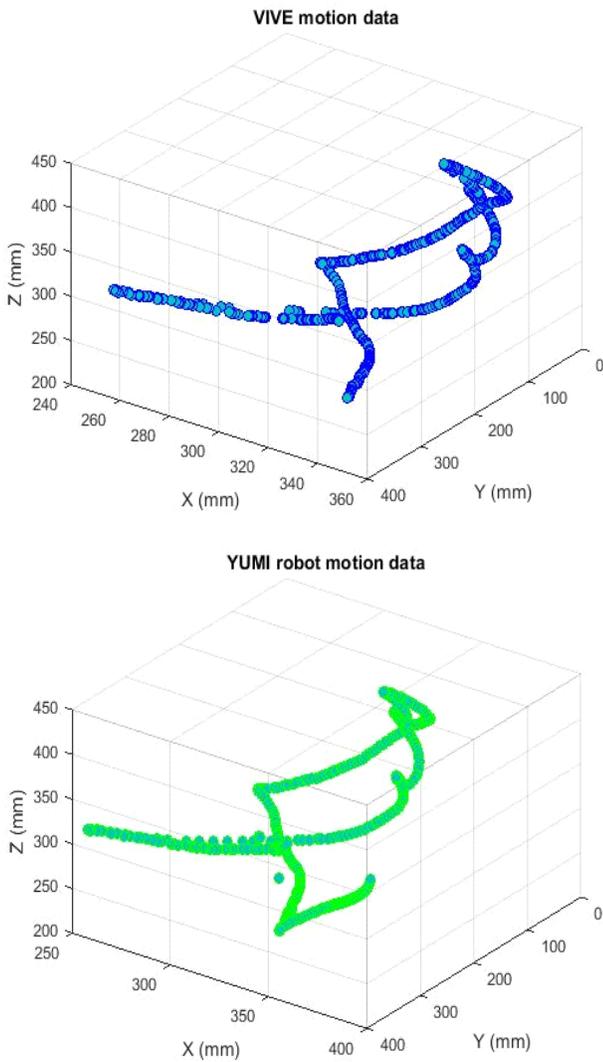


Figure 8. Experiment 2 Motion Data of Vive and Yumi

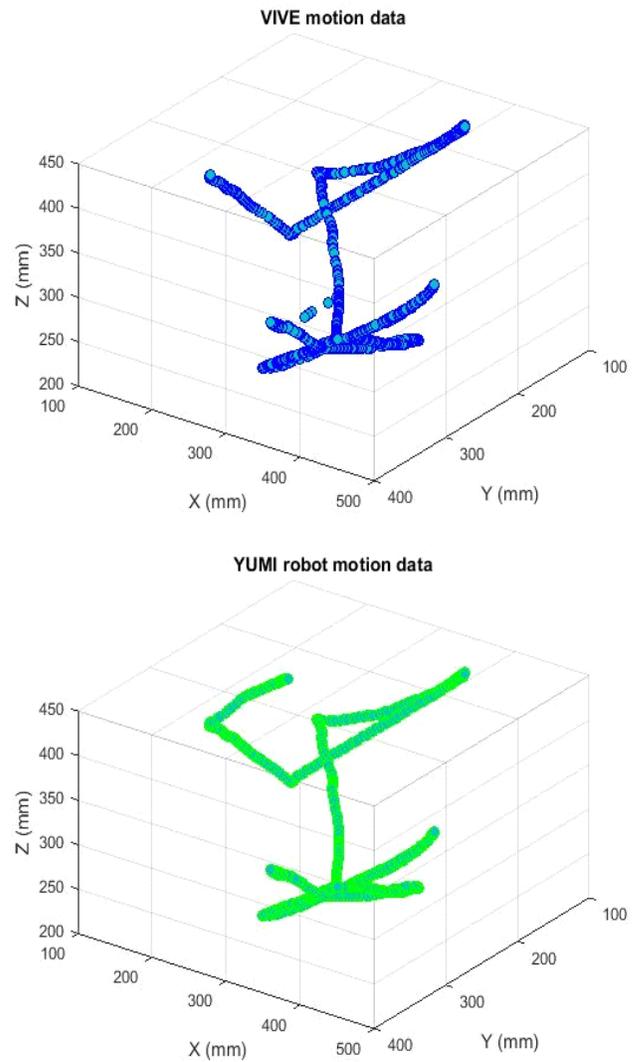


Figure 10. Experiment 3 Motion Data of Vive and Yumi

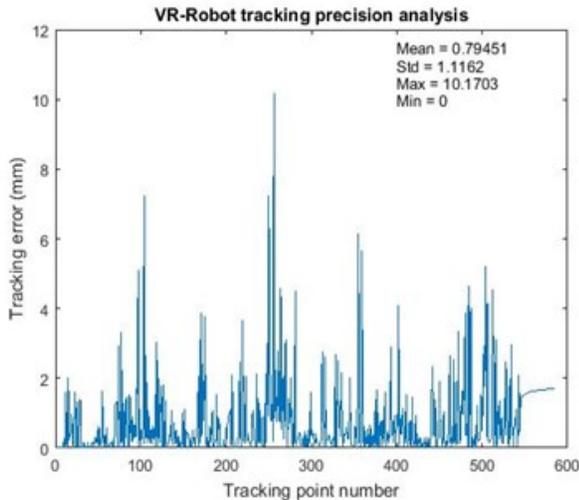


Figure 11. Experiment 3 Tracking Error

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# SMART CHARGING MANAGEMENT SYSTEM OF PLUGGED-IN EVs BASED ON USER DRIVING PATTERNS IN MICRO-GRIDS

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## Abstract

Micro-grid system stability and security is becoming a challenging issue recently, due to the high penetration of renewable energies in power production, such as wind and solar, with respect to their unpredictable nature. Furthermore, the presence of electric vehicles (EVs) in the near future in households is inevitable as EV worldwide popularity is growing. In this paper, the authors propose a smart, real-time control method for plugged-in EV charging by applying smart-grid capabilities. Essential grid constraints regarding overload occurrence prevention, market energy prices, and tracking are taken into account. The proposed control method was evaluated on a modified micro-grid in the MATLAB/SIMULINK environment. Real data of user driving behaviors were taken from previous studies and applied to the current model in order to obtain realistic results. Different worst-case scenarios were derived on a daytime horizon to show the effectiveness of this smart charging method. The results demonstrated the positive impact of this methodology on saving operational costs and increasing system stability.

## Introduction

With the worldwide growing popularity of electric vehicles (EVs), investigation into their available potentials and effects on power-grid operation is inevitable. One such impact could be the extra load that will be imposed on the grid as people plug their cars into the grid and start to charge. This could be very harmful to the grid because of probable overloads and result in higher operational costs, due to expanding the grid and installing new components such as power lines with higher capacity [1]. Therefore, controlling the charging procedure of the EVs, and taking into account essential grid operating constraints, could help overcome this problem and allow grid operators to manage the grid with no additional costs. Furthermore, EV batteries could also be applied for grid-regulation purposes for maintaining grid stability, due to their characteristics of lower energy and quick response time [2, 3] by mean of services such as voltage and frequency regulation [1, 3]. Especially in micro-grids, where most of the power production is de-

livered by renewable energies like wind and solar plants, EV batteries could perform an important role for smoothing their natural intermittency and ensuring grid-wide stability [2, 4, 5].

Applying smart-grid capabilities could provide real-time information about the state of charge (SOC) and the amount of available power capacity from all plugged-in vehicles [3, 6, 7] to help grid operators control their charging procedures and available regulation capacity. An aggregator is necessary to deal with the SOC and plug-in time of the vehicles in order to provide an optimal charging plan to realize minimal operational costs and regulation service for appropriate large-scale power [8, 9]. The minimum and most essential requirement for vehicle owners to join this kind of service is to be guaranteed a satisfactory battery charge by the next time they choose to drive. In addition, some incentives, such as direct payment or lifetime warranty of the battery, should be given for voluntary participation on the part of vehicle owners [10, 11].

## Research Objectives and Methods

As was mentioned in the previous section, developing a real-time smart charging management (SCM) system for EVs could be very attractive for system operators. The main objective of this study was to show how applying this method could help in saving charging costs and increasing system security and stability without limiting EV owner driving behaviors. In this paper, the authors present an SCM method—to handle essential constraints due to overload occurrences—SOC and plug-in state of EVs, next traveling time, and market energy prices. Moreover, system voltage was measured over specific periods to avoid exceeding the minimum and maximum voltage limits [1, 3].

Anytime the system voltage varied from its limits, a signal would bring voltage-compensation facilities into action to overcome the problem. The positive effect of applying this management system for reducing energy costs and maintaining grid stability using the current infrastructure is demonstrated in this paper. The simulated micro-grid and the proposed SCM system are also defined.

## Micro-Grid Test System

Figure 1 shows the micro-grid system used in the MATLAB/Simulink environment. This micro-grid contained wind turbines, solar panels, and a diesel generator for producing power for residential households, an asynchronous machine for the system load, and EVs. Table 1 lists the amount of generation and consumption.

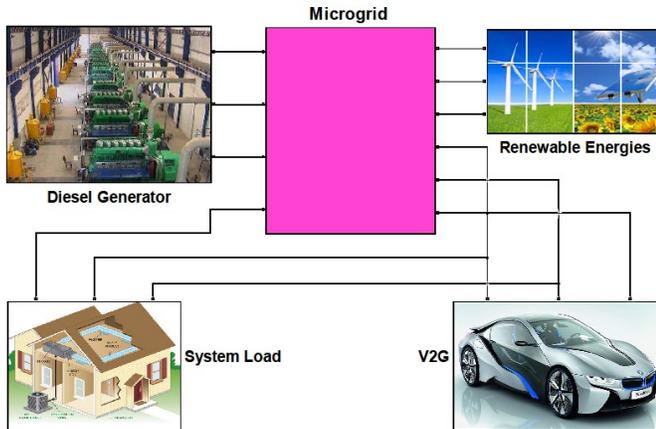


Figure 1. Simulated Micro-Grid System

Table 1. Amount of System Generation and Consumption

Generation Units	Power Generation (MW)
Diesel Generator	15
Wind Turbines	4.5
PV Plant	8
Loads	Power Consumption (MW)
Residential Loads	10
Asynchronous machine	0.16
Electric Vehicles	4

For the following case studies and simulation, it was assumed that the micro-grid operated in an isolated mode so that there would be no power injection from the main grid to the network.

## The Proposed SCM System

Figure 2 demonstrates the proposed SCM system. This system applies different essential control signals, including the SOC of the EVs batteries, the plug-in state of the vehi-

cles, the next traveling time, overload occurrence, regulation market status, and energy market price tracking. Other input signals were also measured using smart-grid capabilities and sent to the SCM system, which creates a charging signal by means of a fuzzy logic controller. In other words, the system decides, according to the fuzzy rules applied to the input signals, when the cars will start charging, thereby obtaining decreased charging costs and preventing probable overload occurrences in the grid and meeting other grid stability constraints.

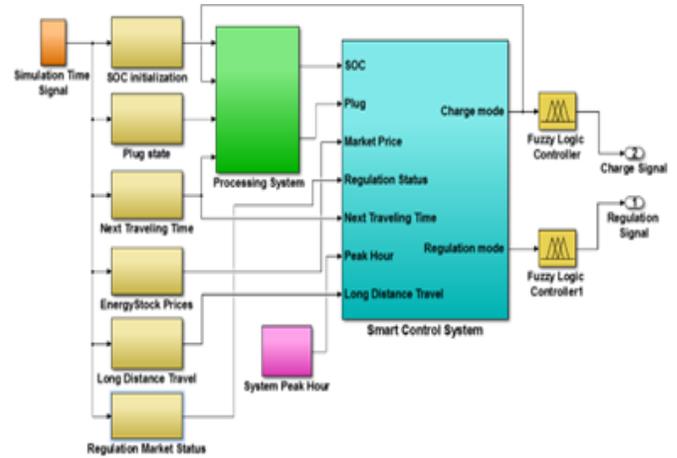


Figure 2. The Proposed SCM System

## Input Signals

The input signals are as follows:

- The SOC signal informs the system of the state of charge of the EVs' batteries during the continuous simulation time (24 hours).
- The "plug" signal refers to the plug-in state of the EVs during the simulation.
- The "market price" signal refers to the hourly energy price that will be called from the German EEX energy stock market in Leipzig, Germany [12].
- The "next traveling time" signal will be determined from the EV owners' supplied data (via smart phone or PC) and the existing database of their driving patterns.
- The "system peak hour" signal receives data from the smart meters about the peak hours of the load curves to prevent overload occurrences and probable blackouts.

Through the smart control system, the input signals are converted to simple digital signals, which lead to faster decision making by the controller. In order to clarify this procedure, two signals are illustrated. In the plug signal, the digit "1" means that the EV is connected to the grid, and

the digit “0” indicates that the EV is not connected to the grid. In the next traveling time signal, if the traveling time is less than a certain amount, the controller converts the signal to a 1 and decides, based on specific criteria, whether or not EVs are charging.

## The Fuzzy Control System

As mentioned previously, a fuzzy logic controller was used to decide when the cars start to charge. Also applied in this study were a series of related fuzzy rules developed for use with membership functions for any input signal. This fuzzy controller could decide the charging status of the EVs, based on the real-time status of the input signals. As an example, if there is currently a high, medium, or low energy price on the market or an overload occurrence, etc., what would be the best charging solution. Figure 3 demonstrates this fuzzy logic controller. The displayed flowchart of Figure 4 describes completely the decision mechanism of this fuzzy controller based on the input signals.

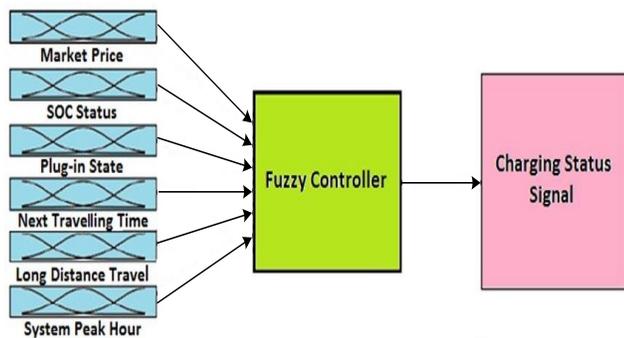


Figure 3. Fuzzy Logic Control System

## Simulation and Results

The simulation of the micro-grid system was run in two different modes to see the positive effect of the proposed SCM system in decreasing charging energy costs. Figure 5 shows a comparison of the amount of charged energy of the EVs both with the SCM system and without it. It can be seen in Figure 5 that the EVs charged energy decreased mostly during two periods in which the SCM system was applied. The first period was from 8:00am until 10:00am, with the other period from 10:00pm until 12:00am. The most decrease of energy charging occurred at 8:00pm, which is predictable, because of the highest energy price at this time of the day. It is also obvious that a charging increase will occur during early morning hours when energy prices are low (load shifting). Based on this figure, if the SCM system had not been used, the car holders would

charge their cars immediately after they arrived home without considering essential constraints like overload occurrence of the grid components or high energy prices. The SCM system did not just shift the charging hours to save costs, though the EVs with high SOC (in this case 85% battery charge) would not charge their cars at medium and high energy prices at all, because it is not necessary to always charge the batteries up to 100% for covering their regular distances. Therefore, the daily charged energy with the SCM was a little less than the amount of energy without the SCM. In case of long trips, the EVs would charge at any energy price to gain a full charge before the trip in order to maintain the driver’s comfort.

In this regard, Figure 6 depicts a comparison of the energy costs. As expected, the energy costs decreased in system peak hours. And, as noted previously, the most cost savings occurred at 8:00pm when energy price reached their highest value during a 24-hour period. It is also worth noting that the charging costs are higher from 12:00pm until 6:00pm or early morning hours, even using the SCM system. These higher energy costs are the result of lower energy prices during these times of day. However, there will still be cost savings during the day, as indicated by the graph in Figures 6 and 7. This cost difference could be better observed in Figure 7, which results in a daily cost saving of up to €162, while applying the SCM system. According to Figure 8, this amount of money could be extrapolated out to a year and would result in annual charging cost savings of around €59,000, which is a considerable amount of money. In addition, due to the SCM system, there are no overloads on the grid after adding the EVs as extra loads, which avoids grid expansion costs.

## Conclusions

These simulation results show the positive effect of applying the proposed SCM system in power grids, especially micro-grids. Through the use of this proposed smart system, the grid operator could avoid extra expansion costs for new grid facilities and components in order to meet the added EVs’ energy requests, due to load shifting and peak shaving. Furthermore, the EV owners saved an annual charging cost of around €59,000, which could be a notable incentive for the owners to plug their cars into the grid whenever they arrive home or have a chance to, so that the cars are always charged and ready for the next trip. These plugged-in EVs could also be applied for grid-regulation purposes, which could help grid operators in saving regulation costs and maintaining a stable grid with existing infrastructures. These services will also bring in additional income for the EV owners. A Smart regulating system could be investigated in future studies.

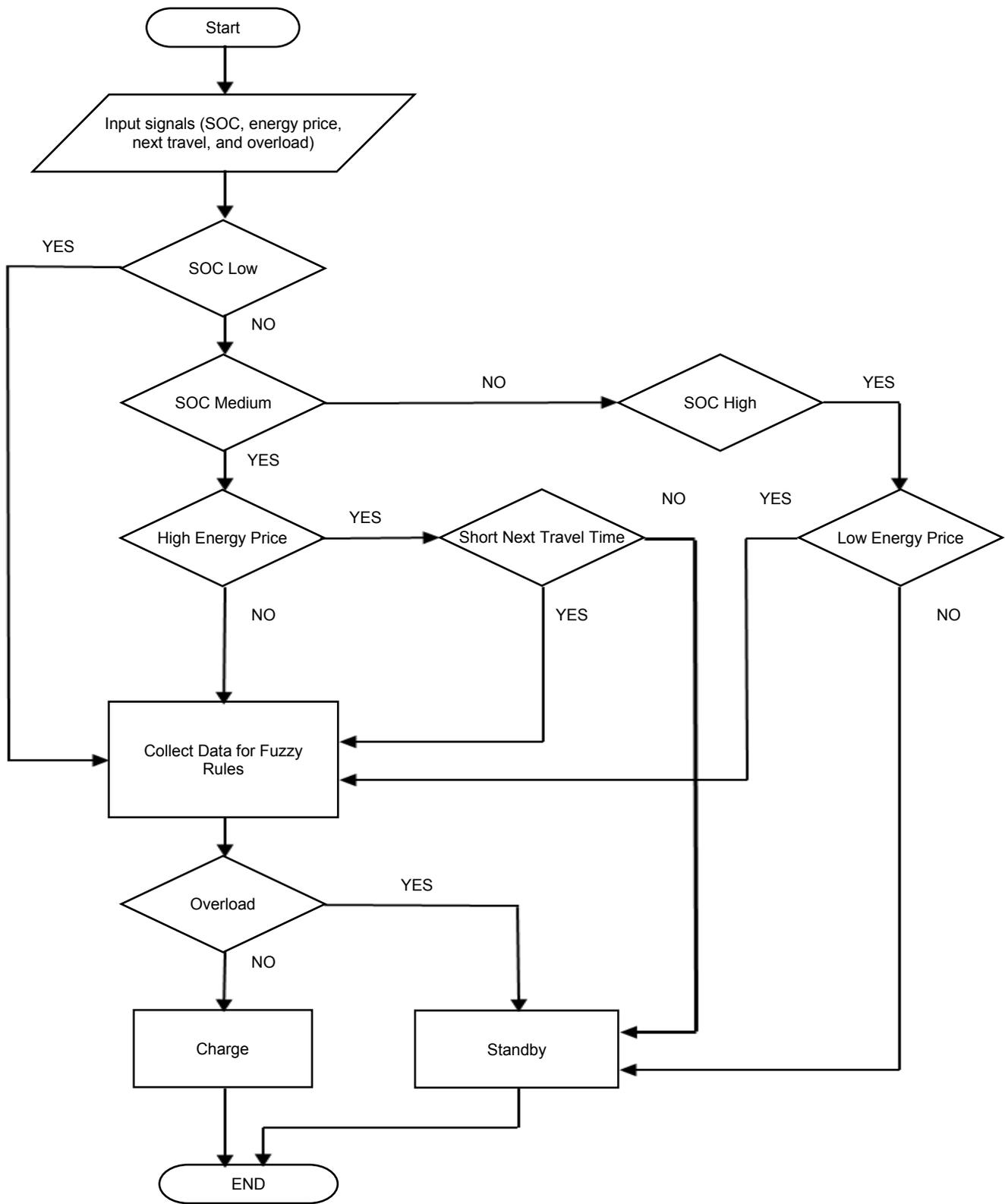


Figure 4. Fuzzy Logic Control System Mechanism



Figure 5. EV Daily Charged Energy with and without the SCM System

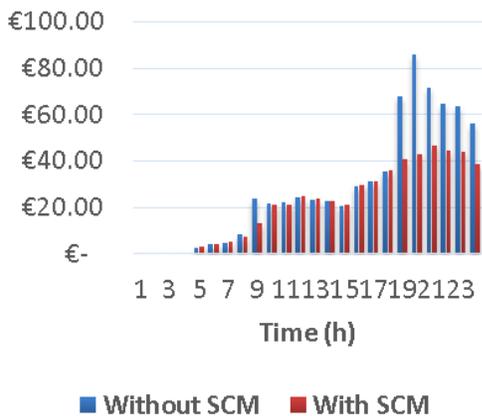


Figure 6. EV Daily Energy Costs

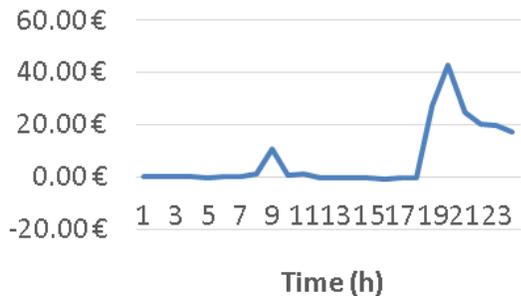


Figure 7. Daily Charging Cost Difference of the Two Modes



Figure 8. Annual Charging Cost Comparison

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# REDUCING ENERGY USE AND INCREASING WIRELESS SENSOR NETWORK SECURITY USING A COMBINATION OF PARTICLE SWARM OPTIMIZATION AND HASH ALGORITHMS

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## Abstract

The aim of this study was to reduce energy consumption and increase wireless sensor network security by combining PSO and HASH algorithms. Recent developments in electronic and wireless communications have led to the production of all-purpose sensor nodes that are small, suitable for short distances, and have low power consumption and production costs. Sensor networks are one of the most important technologies in the 21<sup>st</sup> century, as they have widespread applications: Ease of use; low installation costs; distribution in large areas; and, high resistance. They also have growing applications in homes, industry, and military sectors. This current study was analytical and practical and was conducted using the combination of PSO and HASH algorithms in order to reduce energy consumption and increase wireless sensor network security. Based on game theory, this study was carried out modeling sleep/wake-up nodes. Using the LEACH protocol, energy is distributed through a network. Each cluster head shows itself to the other nodes that are selected, and each node selects an appropriate CH. The results of the study showed that with the assumption that for some sensors more energy was considered, the SEP protocol was more efficient than LEACH in optimizing efficiency features.

## Introduction

Recent developments in the electronic field and wireless communications has resulted in the production of all-purpose sensor nodes that are small, appropriate for short distances, and consume very little power. According to the theory of wireless sensor networks, these small sensor nodes are included in sensing, data processing, and data transferring equipment [1]. Their ease of use, low installation costs, wide distribution, and high resistance are among the advantages of sensor networks [2]. Sensor networks are, in fact, the accumulation of a large number of sensor nodes dispersed in the environment, each of which, independently or in relation to other nodes, has a particular purpose [3]. The nodes are close together, are able to communicate with each other, can share their information with other nodes,

and the status of the monitored environment is sent to a central node [4].

Due to limitations related to high power consumption in sensor networks, a large number of sensor nodes within a dense array are placed in a dynamic and variable topology that leads to the movement of the nodes. Nodes also communicate with each other directly and without any access to each other or being organized. As a result, in these networks, nodes continuously change their position. In order to identify a path, they need a routing protocol that can adapt itself to these changes. In these networks, routing and security are important and require forming and designing a set of network protocols that perform various functions of network control and management, such as coordinating and synchronizing, node positioning, and network security. The use of traditional routing protocols in wireless sensor networks faces the challenge of energy limits in these networks. Energy consumption can be reduced by simulating sleep/wake-up nodes based on game theory [5].

In order to optimize energy consumption in sensor networks, it is necessary to increase their error tolerance, since errors are inevitable and cause loss of energy, physical failure, and hardware and software problems that can cause the sensor networks to incorrectly perform their tasks. Therefore, using a particle swarm optimization algorithm (PSO) in sensor networks can increase error tolerance [6]. Today, managing and optimizing energy consumption is very important. Doing this, however, can save energy in wireless sensor networks that have limited storage space. In most applications, the primary energy sources of networks are not rechargeable, so energy optimization can reduce energy consumption and increase the life of the network nodes. In this regard, and in order to store energy, some techniques will be introduced that are included in routing protocols in sensor networks that are based on power management and the way communication takes place between parent and child nodes, while considering the distances between them [7]. In fact, in wireless sensor networks, energy is stored in order to manage power by turning off the radio unit in the inactive nodes. There are also several ways to use this method.

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One common and efficient way is to put some of the nodes in sleep mode [8]. Thus, in designing the hardware nodes, the use of designs and components that have low-energy consumption is important, since it makes it possible to provide a sleep mode for all of the nodes or for each independent segment. The second method is to adjust the transferring area to the width of the neighbor node, so that in order to sense and transmit information, only the distance from the neighboring node is required [9]. At present, distance-and-energy-aware routing with energy reservation is one of the most important research areas in sensor networks. Increasing network lifetime is the biggest challenge in this type of network [10].

The purpose of this current study was to introduce successful hierarchical clustering algorithms for routing in wireless sensor networks in order to increase the lifespan of these types of networks. To do this, in customizing this algorithm for routing, two criteria for reducing energy consumption and the proper distribution of energy between sensor nodes was considered and which led to a longer network lifetime. This current study was an application of analytical-applied research, which aims to reduce the energy consumption and increase the security of wireless sensor networks by combining particle swarm optimization (PSO) and HASH algorithms.

## The Particle Swarm Optimization (PSO) Algorithm

The PSO algorithm increases the error tolerance in sensor networks by optimizing the cost function. It is performed in a way that the velocity vector of each particle is updated by this algorithm and then the new speed value is added to the position or magnitude of the particle. Thus, updating velocities is influenced by both values of the best local answer and the best absolute (value) answer. In fact, the best local answer and the best absolute answer are the best answers up to the moment of executing the algorithm obtained by a particle and in the whole population, respectively. The main advantages of executing the algorithm are its ease of use and the presence of input parameters of the PSO algorithm.

## Using the HASH Algorithm to Secure Information

The HASH algorithm is a method for checking data integrity, and is also a one-way function that performs a digest operation on the stream of input data. In contrast with data encryption, this one-way algorithm converts Clear text into text. The larger the Clear text, the more enhanced the cipher volume will be. Furthermore, this algorithm converts the

input data stream into a small digest. This is a one-way operation (irreversible) and the flow of input data with any volume is the output of a constant value. This algorithm uses a string with a different length as input and creates an "MD5 message digest" or "fingerprint" with a length of 128 bits. The most famous HASH methods are (8):

- (MD5) In this algorithm, the created digest is 128 bits.
- (SHA-1) In this algorithm, the generated digest is 160 bits.
- (SHA 2) In this algorithm, the generated digest can be between 224 and 512 bits.
- One of the algorithms of HASH is the sender vehicle algorithm.

## Game Theory

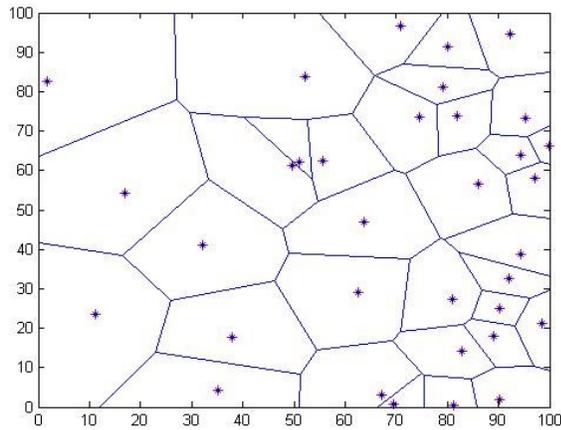
Game theory is defined through an all-pervasive mode and is expressed to collect mathematical models, study the location of the collision, and present a cooperative model in the form of mathematical formulas. On this basis, it is possible to make good decisions by choosing locations, detecting sustainable results, and identifying the best-performing activity. A number of elements are involved in defining locations existing in game theory:

- The existence of two small players. These players include a person, company, country, and wireless nodes.
- Each player can have a number of sustainable strategies, intermittent activity, or the choice of a stream. The strategy chosen by each player is determined by the result of the game.

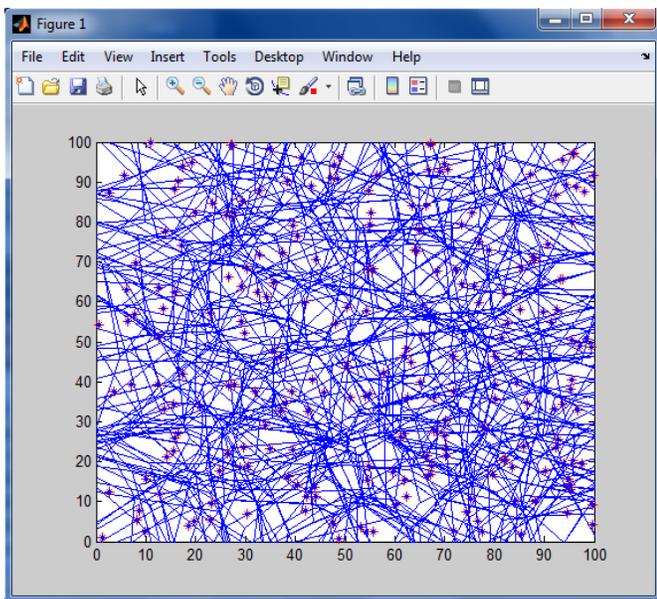
Considering each result of the game, mathematical audits are performed by each player. These audits provide a range of results related to each player. The value of these results is different for each player. In the design and operation of wireless sensor networks, game theory has a supportive role that demonstrates how to communicate between wireless sensor networks and game theory.

## Simulating the LEACH Protocol

Figure 1 shows the results of simulating the LEACH protocol and indicates the primary clustering in the protocol immediately after the start of the first round. Figure 2 shows the asterisks, which are sensor nodes selected in the first step as the cluster head. After repeating different rounds of the algorithm and sequential changes in cluster heads and multiple routing for these cluster changes, the multiple paths for transmitting information after 20 rounds are obtained (see again Figure 2).

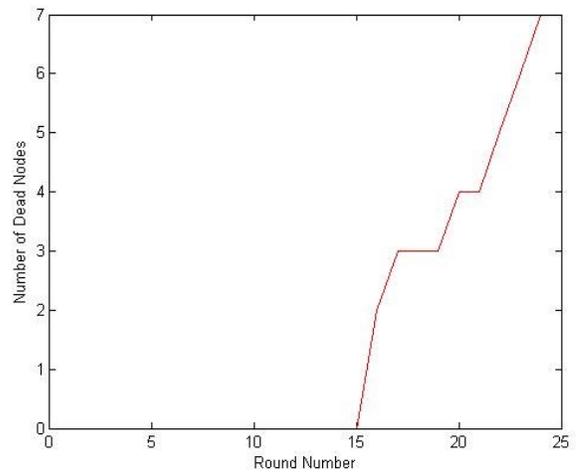


**Figure 1. Primary Clustering of the LEACH Protocol**

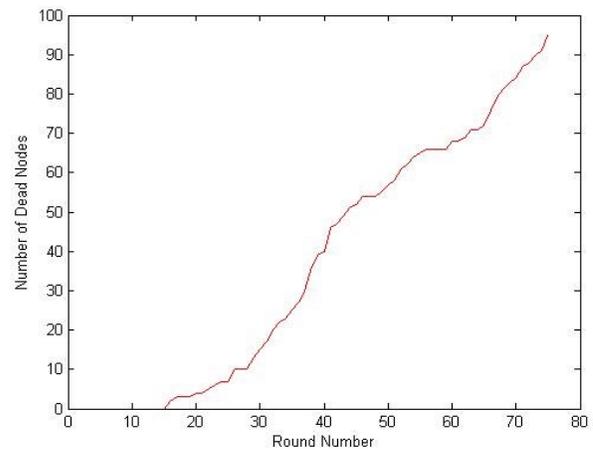


**Figure 2. Selected Cluster Heads and Routing for 20 Rounds**

According to the results, the cluster heads changed dynamically and were selected in different rounds. This way, energy consumption was distributed over the entire network. Figure 3 shows that, after 25 rounds of running the algorithm, the energy was about seven knots lower than the threshold. In other words, there are seven dead nodes. The death of the first node occurred in the fifteenth round; and gradually from the fifteenth round to the twenty-fifth round, the number of dead nodes increased from one to seven. This process illustrates the principle that by increasing the number of rounds of executing the algorithm, the number of dead nodes will also increase. Figure 3 shows the number of dead nodes after 25 rounds, and Figure 4 shows the number of dead nodes after 80 rounds of running the algorithm.



**Figure 3. The Number of Dead Nodes after 25 Rounds of Executing the Algorithm**

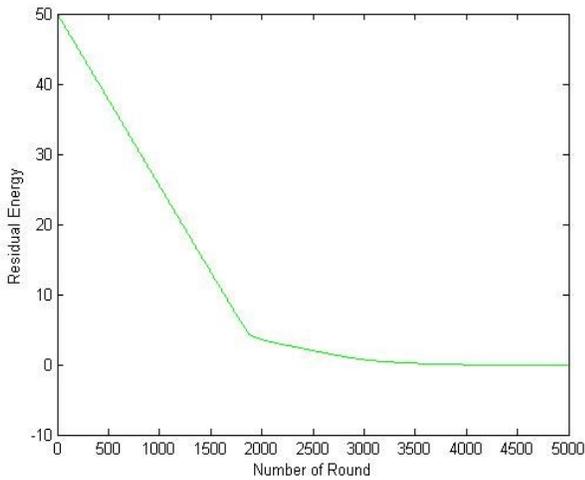


**Figure 4. The Number of Dead Nodes after 80 Rounds of Executing the Algorithm**

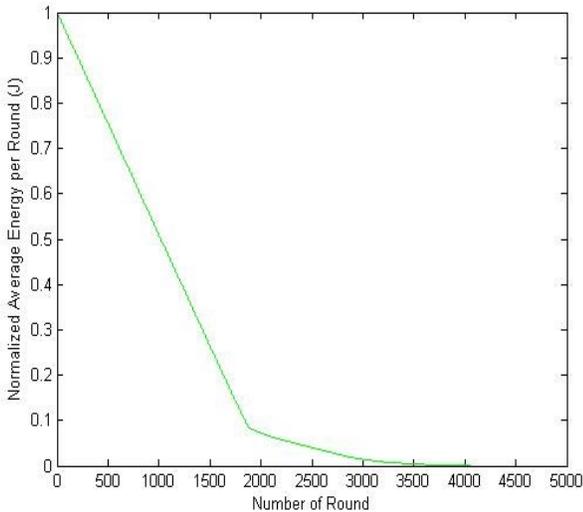
The total number of nodes was determined by simulating 200 nodes. Figure 3 shows that, after 80 rounds, the number of nodes was about 100 (half the total number of nodes). According to the results, after about 25 of the 100 rounds of simulation, an average of 40% of the primary energy of the network nodes was consumed. This indicates the high energy consumption of the sensor network in its early stages in the LEACH protocol. The results also showed that, after about 70 rounds of executing the algorithm, more than 85% of the energy of the sensor network nodes was consumed. This shows the weakness of the LEACH protocol in terms of energy consumption and, consequently, the lifespan of the network. With the high energy consumption of the nodes in the network, the life of the network will decrease accordingly.

## Simulating the SEP Protocol

The SEP protocol is the optimized version of the LEACH protocol, which integrates the network nodes in a chain in order to route the data to the destination node. In the following section, the simulation related to the protocol is shown. Figure 5 shows the remaining energy of the nodes in the SEP protocol over many rounds. As can be seen, after about 2000 of the 5000 rounds defined for the algorithm, the average energy remaining for the sensor nodes in the SEP protocol has reached zero. Figure 6 shows the results of having normalized these numbers for comparison with the LEACH protocol.

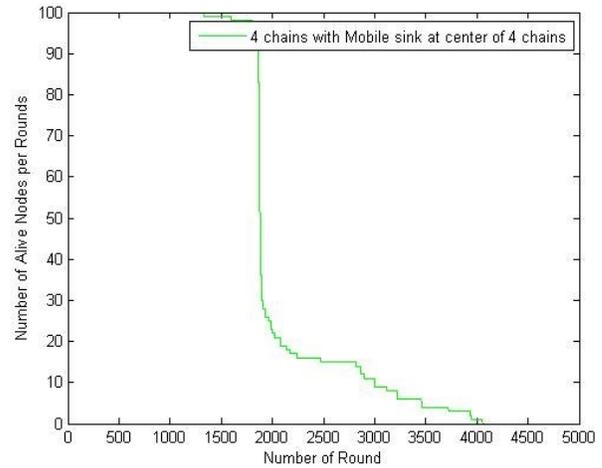


**Figure 5. The Remaining Sensor after 5000 Rounds**

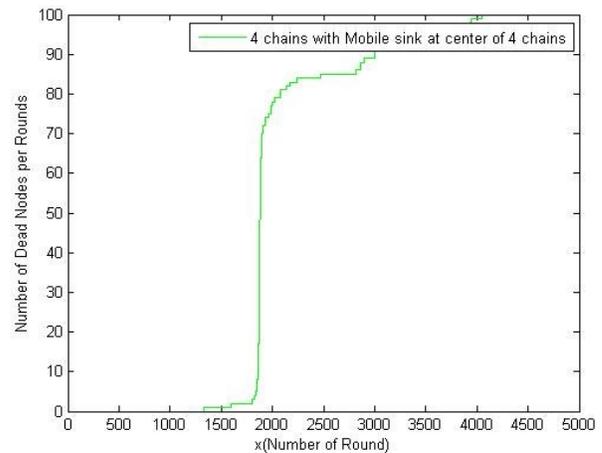


**Figure 6. The Normalized Remaining Energy**

It should be noted that, in the above comparison, the primary energy of the nodes was 0.1 and the number of rounds was 100. Also of note is that the SEP protocol significantly reduced the energy consumption of the nodes, when compared with the LEACH protocol. Figures 7 and 8 show the number of live and dead nodes over multiple rounds, respectively. Figure 7 illustrates this important issue, that in the two-thousandth round, the number of live and dead nodes changed significantly. This important point shows that the sensor network provided under the SEP protocol will be efficient up to 2000 rounds. In other words, the lifespan of the network is 2000 rounds. Furthermore, the number of dead nodes in the 2000<sup>th</sup> round increased significantly. According, it can be said that the SEP protocol has solved the problem of energy consumption and the lifetime of the network (see Table 1).



**Figure 7. The Number of Live Nodes over Multiple Rounds (SEP Protocol)**



**Figure 8. The Number of Dead Nodes after 5000 Rounds**

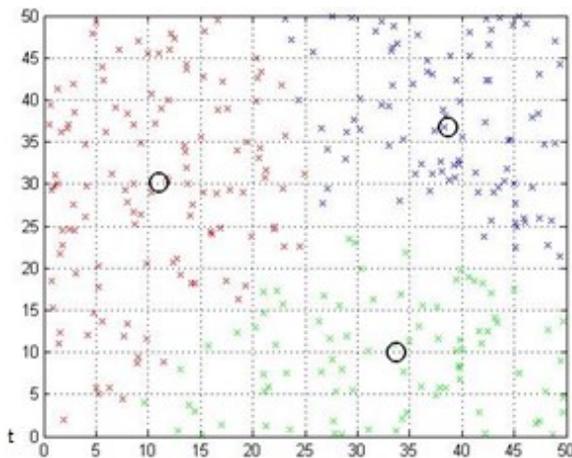
**Table 1. Comparing the LEACH and SEP Protocols in Terms of Average Remaining Energy**

protocol	Average remaining energy (after 100 rounds)
LEACH	0.1
SEP	0.9

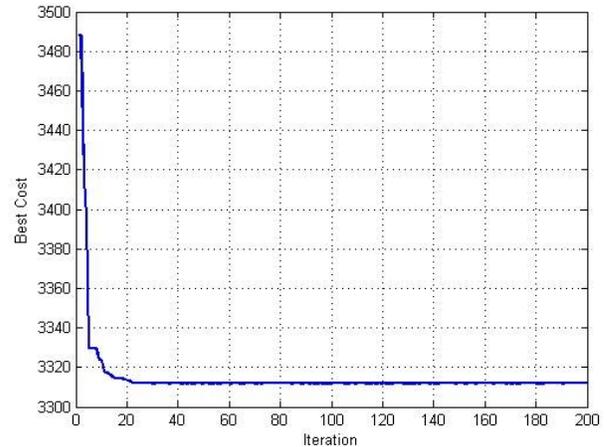
## Simulating the Method

In this study, the authors looked for a method for reducing energy consumption in sensor networks. To this end, the efficiencies of the PSO and HASH algorithms were used. In this simulation, the number of clusters and, consequently, the number of cluster headers was considered to be three. The selection process for the cluster heads was assigned to the HASH algorithm. Figure 9 shows that the convergence process, in clustering the sensor network, the PSO algorithm was effective, since it minimized the repetition of the target set of functions defined for clustering. This shows that the PSO algorithm successfully clustered the wireless sensor network.

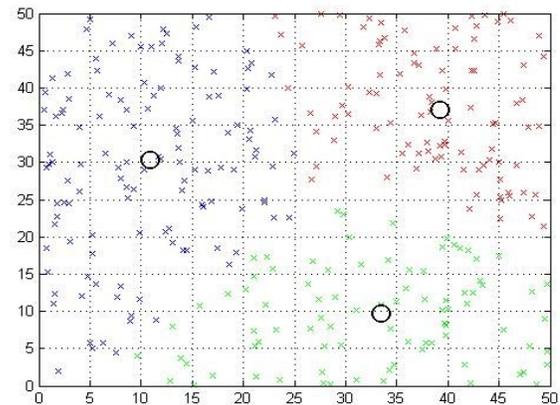
Figure 10 shows how the algorithm was optimized in the 25<sup>th</sup> repetition; thus, the algorithm was considered efficient. To prove the efficiency of PSO, the HASH algorithm was also used for clustering this network. This way, the efficiency of the algorithm used in sensor network was tested. Figure 11 shows the clustering of the HASH algorithm and Figure 12 shows its convergence process. By examining these two figures, the superiority of the PSO algorithm in minimizing the number of target set function repetitions was clearly demonstrated.



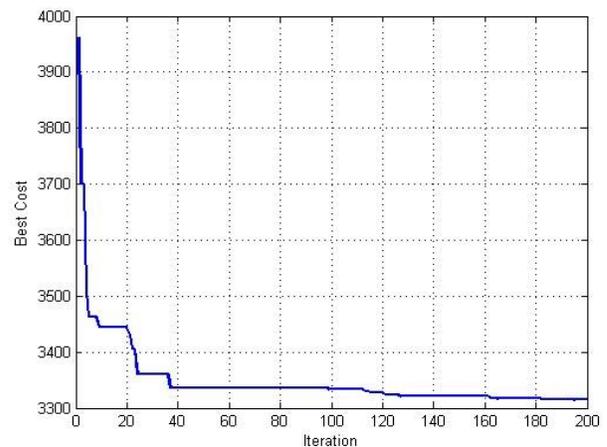
**Figure 9. Clustering of the Sensor Network Nodes Using the PSO Algorithm**



**Figure 10. Convergence Trend of the PSO Algorithm for Wireless Sensor Network Clustering**



**Figure 11. Clustering Using the HASH Algorithm**



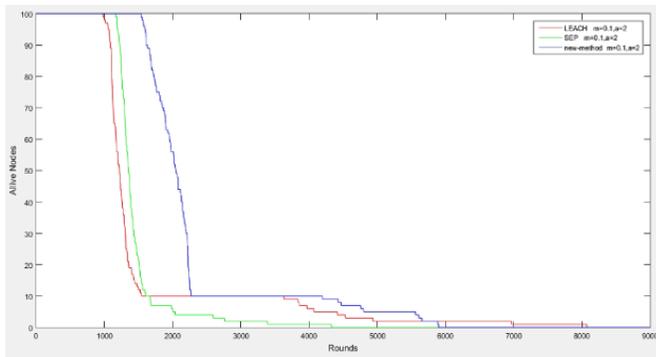
**Figure 12. Convergence Process of the HASH Algorithm**

The results showed that the HASH algorithm reaches the defined optimality criterion after about 180 repetitions. Therefore, it can be said that the performance of the PSO algorithm in clustering was largely acceptable. The next step was devoted to choosing the clusters and securing the routing of sensor networks by using a comparative algorithm. Table 2 shows the parameters used in the simulation.

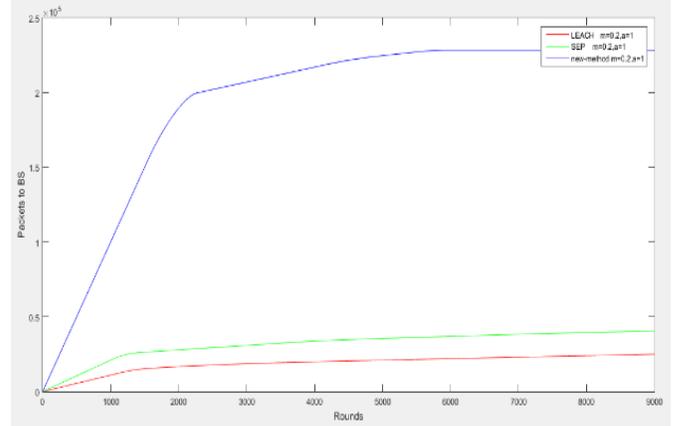
**Table 2. Parameters Used in the Simulation**

Parameters	Quantities
Primary energy $E_0$	0.5 J
Primary energy of favorable nodes	$E_0(1+\alpha)$
Energy for $E_{DA}$ data accumulation	5 nJ/bit/signal
Received and sent energy $E_{LEC}$	5 Pj/bit
Reinforcing energy for short distances $E_{FS}$	10 Pj/bit/m <sup>2</sup>
Reinforcing energy for long distances $E_{AMP}$	0.013 Pj/bit/m <sup>4</sup>
Probability $P_{opt}$	0.1

Figure 13 shows the number of live nodes in each round. Obviously, in the proposed method, over time, the number of live nodes is greater than those for the SEP and LEACH methods. Since the LEACH method is very sensitive to heterogeneity, the node dies at a rapid pace. The SEP algorithm performs better than the LEACH algorithm. The proposed method performs better than the other two methods, because the nodes are directly connected to the base station in the 0 zone (normal node). Comparing the power and energy remaining in each node for each of the three algorithms showed that, in the long term, the behavior of the proposed method was much better than the LEACH and SEP protocols. Table 3 shows the results for energy consumption for all three algorithms. This table also shows that, after 105 rounds, the combined PSO and fuzzy algorithm had the best result.



**Figure 13. Number of Live Nodes per Round**



**Figure 14. Power in Any of the Three Algorithms**

**Table 3. Results of the Three Algorithms after 105 Rounds**

Method	Power after 105 rounds
LEACH	1165
SEP	2226
PSO	10600
PSO & HASH (New Method)	68150

## Scalability

In this section, for the intended algorithms, some parameters were changed. Table 4 shows the results of the obtained power.

**Table 4. Comparison of Power Outputs**

Parameter	LEACH	SEP	PSO and HASH	PSO
Page coordinates (100,100) Base station coordinates (50,50) Node = 100	1954	2189	23745	3258
Page coordinates (100,100) Base station coordinates (50,50) Node=50	589	898	8321	1287
Page coordinates (1000,1000) Base station coordinates (500,500) Node = 250	2214	2674	41235	11221

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## Conclusions

In this study, the authors tried to reduce the energy consumption in wireless sensor networks with respect to the capabilities of the evolutionary algorithms in optimizing the defined target set of function (codomain) and fuzzy logic. To do this, they first studied the LEACH and SEP protocols, which would later be compared with the proposed algorithm. In this way, the PSO algorithm was used to optimize the clustering and the PSO and HASH combination algorithm was used to select cluster heads. Finally, according to the results of the proposed algorithm, the energy consumption was reduced by 80%, when compared with the LEACH algorithm, and reduced by 5%, when compared with the SEP protocol.

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## Biographies

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**MOHAMMAD HOSEIN SHAFIABADI**

# DEVELOPMENT AND EVALUATION OF CYBERSECURITY EDUCATION GAMES FOR HIGH SCHOOL STUDENTS

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## Abstract

Cybersecurity workforce development is the key to protecting information and information systems, and yet more than 30% of companies are short on security expertise. To address this need, the current authors have developed four cybersecurity education games to teach social engineering, secure online behavior, cyber defense methods, and cybersecurity first principles. These games are intended to recruit the next generation cybersecurity workforce by developing an innovative cybersecurity curriculum and pedagogical methods to provide high school students with hands-on activities in a game-based learning environment. Purdue University Northwest (PNW) offered high school summer camps for 181 high school students in June of 2016 and June of 2017. Out of 181 high school participants, 107 were underrepresented minority students, including African Americans, Hispanics, Asians, and Native Americans. To evaluate the effectiveness of the cybersecurity education games, post-camp surveys were conducted with 154 camp participants. The survey results indicated that the games were very effective in cybersecurity awareness training. Furthermore, the cybersecurity education games were more effective for male students than female students in raising student interest in computer science and cybersecurity.

## Introduction

With the recent high-profile cybersecurity incidents targeting Sony Pictures, Target, and Anthem, and the massive Office of Personnel Management (OPM) government data breach that followed, cybersecurity has become a top priority for the U.S. government. Cybersecurity is a shared mission between government and industry, because a large portion of the national cybersecurity infrastructure is in the private sector. Over the past few years, millions of gigabytes of sensitive data have been compromised, and a large number of fraud incidents have been committed, especially in the financial and healthcare sectors [1, 2]. Such security breaches not only result in substantial financial losses, but also greatly hurt the confidence of customers, business partners, and stakeholders [3]. Cybersecurity workforce development is the key to ensuring that a nation has adequate

security measures to protect and defend its information systems. However, a global shortage of 1.8 million cybersecurity professionals by the year 2022 has been estimated [4]. According to the U.S. Bureau of Labor Statistics, the growth rate of jobs in information security is projected to be 37% between 2012 and 2022 and, thus far, more than 209,000 cybersecurity jobs in the U.S. have gone unfilled every year. The increasing demand for cybersecurity professionals requires collaborative efforts from government, industry, and K-12 and higher education institutions to attract, prepare, and train future cybersecurity professionals.

Cybersecurity has become a top priority for the U.S. government. The U.S. government and major legislative proposals have been passed to enhance U.S. cybersecurity and new government agencies have been proposed to combat cyber threats. The U.S. Congress has urged that it is critical to develop high-quality educators to expand cyber education at an early age [5]. Expanding cybersecurity education to high schools is sorely needed, as “the key to training more cybersecurity experts... is exposing students to STEM education... as well as adding some cybersecurity training in high school” [6]. The National Security Agency (NSA) and National Science Foundation (NSF) have jointly funded more than 300 summer camps for K–12 students and teachers across the nation over the past three years [7].

Research indicates that students receiving computer education in high school are eight times more likely to major in a computer degree; yet, in the last 20 years, enrollment in computer education courses has seen a dramatic decrease at the high school level [8]. In addition, student participation does not align with overall national demographics. These statistics indicate that the key to developing more graduates in the cybersecurity field is establishing a meaningful pathway earlier in the educational process and making it accessible to all students. A primary challenge to achieving this goal is the lack of age-appropriate cybersecurity curricula implemented with pedagogical methods that are most conducive to learning at the high school level [5].

Studies have shown that students tend to retain only 20% of what they hear and read, but can retain 90% of what they have practiced [9]. Traditional teaching uses lectures as the

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major vehicle to deliver scientific knowledge and technology to learners, which has proven to fall short for learners. Learners at the high school level experience greater learning gains if they are given opportunities to actively engage in classroom activities that support the development of critical thinking and problem-solving skills. Therefore, there is a critical need for curricula that use innovative pedagogical methods in the area of cybersecurity education.

Computer-assisted instruction (CAI) comes in many forms, and one of the most popular emerging methods is commonly referred to as “game-based learning.” As its name suggests, this method uses computer games to immerse learners in an artificial or simulated game environment, while experiencing it as real. Game-based learning includes virtual reality games, web-based games, multi-user virtual environments (MUVES), massively multiplayer online games (MMOs), and simulations [10]. To date, however, applying game-based learning instructional methods to cybersecurity education has been limited [11].

Starting in 2016, Purdue University Northwest successfully launched four GenCyber summer camps for 181 high school students, with 107 participants from underrepresented minorities (e.g., African American, Hispanics, Asians, and Native Americans). The PNW GenCyber camp developed innovative game-based cybersecurity education modules to provide high school students with hands-on activities in an immersive learning environment. Included were virtual reality (VR) 3D games, robotic programming games, and practical ethical hacking and cyber forensics labs based on simulated cases for cybersecurity training for high school students. Such game-based cybersecurity education is extremely beneficial to the future cybersecurity workforce, as it exposes more high school students to cybersecurity career pathways at a time when they are making decisions regarding higher education. The innovative pedagogical methods and age-appropriate game-based learning curriculum has made cybersecurity concepts more accessible to students of varying ability levels. This was supported by the post-camp survey answered by 154 participants (return rate of 85%).

## Research Method

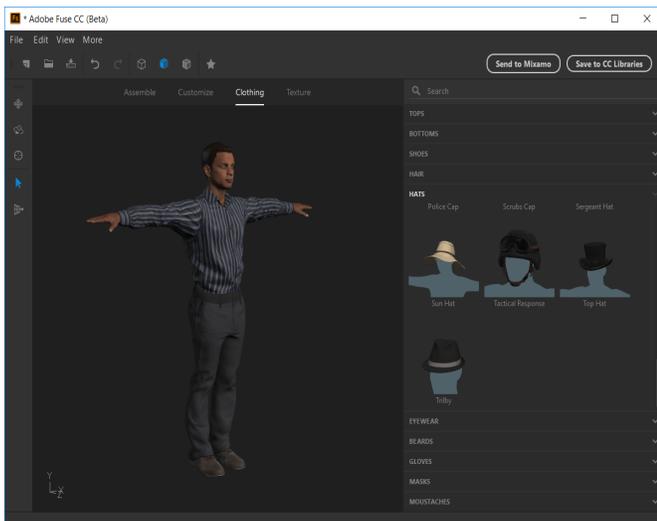
The primary goals of the GenCyber high school summer camp were to: “1) increase interest in cybersecurity, 2) raise general awareness of cybersecurity and help all students understand appropriate and safe online behavior, and 3) increase diversity in the US cybersecurity workforce” [12]. To raise general awareness of cybersecurity and safe online behavior of high school students, PNW developed cybersecurity education games to meet the GenCyber program goals, which included the following:

1. **Social engineering game:** Social engineering is the art of manipulating people so that they give up confidential information, and social engineering scams such as phishing emails have been extremely effective in security attacks. The PNW GenCyber camp implemented a 3D VR game to simulate piggybacking, tailgating, and mantraps in a security-enhanced office environment to raise general awareness of social engineering scams.
2. **Secure online behavior game:** Secure online behaviors include identifying phishing emails and appropriately handling them, distinguishing between trustworthy web links and insecure links, handling fraudulent phone calls, and protecting personal information. A 3D VR secure online behavior game was developed to simulate a high school computer lab and a typical student’s bedroom environment. The secure online behavior game allows students to explore how to appropriately handle email messages, text messages, Web links, and phone calls, using various computing devices such as school computers, mobile phones, laptop computer, and networked game consoles.
3. **Cyber Defense Tower Game:** Tower defense game is “a subgenre of the strategy game to defend a player’s territories or possessions by placing defensive structures on or along their path of attack” [13]. A Cyber Defense Tower Game was created to allow students to protect their virtual computer server from the different cyber-attacks by applying GenCyber first principles and cybersecurity knowledge. During play, students need to select the correct type of defense towers to stop each wave of cyber-attacks. As the game progresses, the combinations of different cyber-attacks come faster and become more complex, making it more difficult for students to defend their servers.
4. **2D GenCyber Card Game:** The GenCyber card game is a computerized version of the physical GenCyber card game [14]. The physical GenCyber card game requires two players to play the game, while the computer-based GenCyber card game is a single-player adaptation, allowing the student to use the game for self-study at any time.

Through their research, the authors also created a number of case studies based on the following digital simulation and modeling tools in both the mechanical and electrical engineering technology fields.

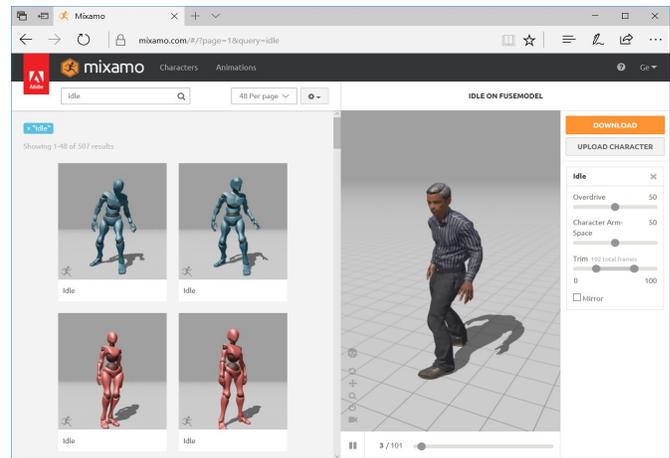
## Development of Social Engineering and Secure Online Behavior Games in Unity3D

Social engineering and secure online behavior games were developed in the Unity3D game engine. Both games can be classified as 3D Role-Playing-Games (RPG). The development of the 3D RPG cyber security game consisted of three major technical components: 1) 3D character and game environment modeling, 2) animation of the 3D game characters, and 3) scripting/programming of the interaction between game characters and dynamic behaviors. The 3D characters were created using Adobe Fuse software. Instead of modeling a 3D character from scratch, Adobe Fuse allows a user to assemble a 3D character from more than 20 base characters and further customize it with different weight, height, skin tones, and texture (see Figure 1).

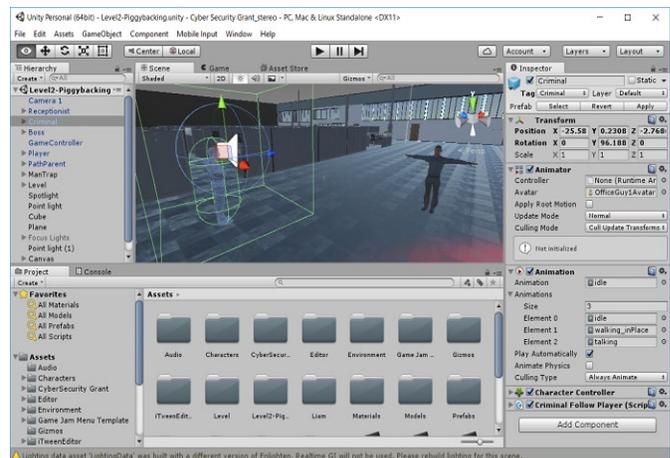


**Figure 1. 3D Character Modeling and Customization in Adobe Fuse**

The 3D character created in Adobe Fuse was transferred seamlessly into the Mixamo software (see Figure 2). Mixamo offers hundreds of different motion clips that can be used in animation, so essential motion clips (such as idle, walk, run, talk, sit, and stand) were chosen for each character and exported to the Unity3D game engine. The game environment was modeled mostly using the royalty-free 3D assets from Unity Marketplace, although several 3D assets that related with social engineering and secure online behavior were modeled using Autodesk 3D Max and Maya software. The behaviors of the 3D game characters were implemented by programming Unity C# script for each character and dynamic assets in the game environment (see Figure 3).



**Figure 2. Character Animation in Mixamo**



**Figure 3. Programming Interactions and Dynamic Behaviors Using Unity C# Script**

The social engineering and secure online behavior games required 3D characters to walk, talk, and make unique gestures. To animate a game character in RPG-style games, an animation component was added to the imported 3D character asset, providing these essential movements to the character so that a game player can control and animate the 3D virtual character in different situations (see Figure 4). To make the virtual game character perform different actions based on the input event, a “Box Collider” from the Unity Inspector control panel was added to the character to trigger different animations when another character entered the Box Collider area (see Figure 5). A character control C# script was also programmed to allow a 3D character to behave differently based on the input event used. Figure 6 shows a simple dialogue script that was applied to a game character. The character will repeat “idle” motion until a game player approaches a non-player character. If a game player enters the Box Collider region, the character will start to talk with the game player by triggering a “talking” animation clip.

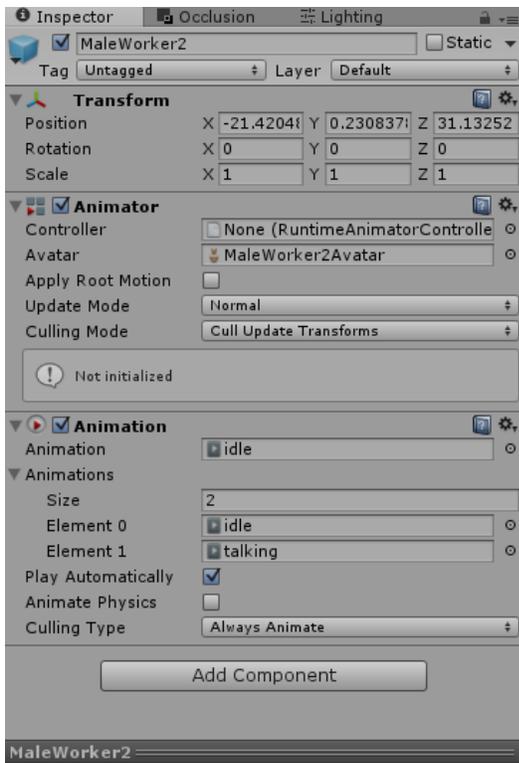


Figure 4. Adding Animation Component to a 3D Character in the Unity Game Engine

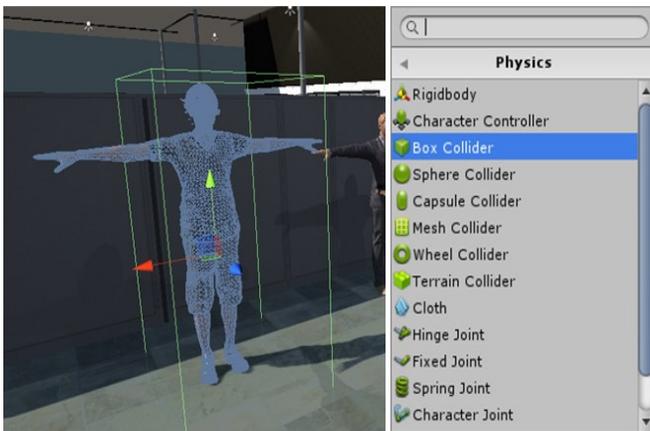


Figure 5. Adding a Box Collider to a 3D Character

The simple dialogue script was added to the 3D game character through the Unity Inspector control panel. Figure 7 shows examples of public variables that can be assigned or modified in various situations. The “Player” variable controls the game player that can interact with the 3D character, and the “Question” variable provides the content of a dialogue between the game player and a non-player character. Figures 8 and 9 were captured from the social engineering and secure online behavior games, respectively.

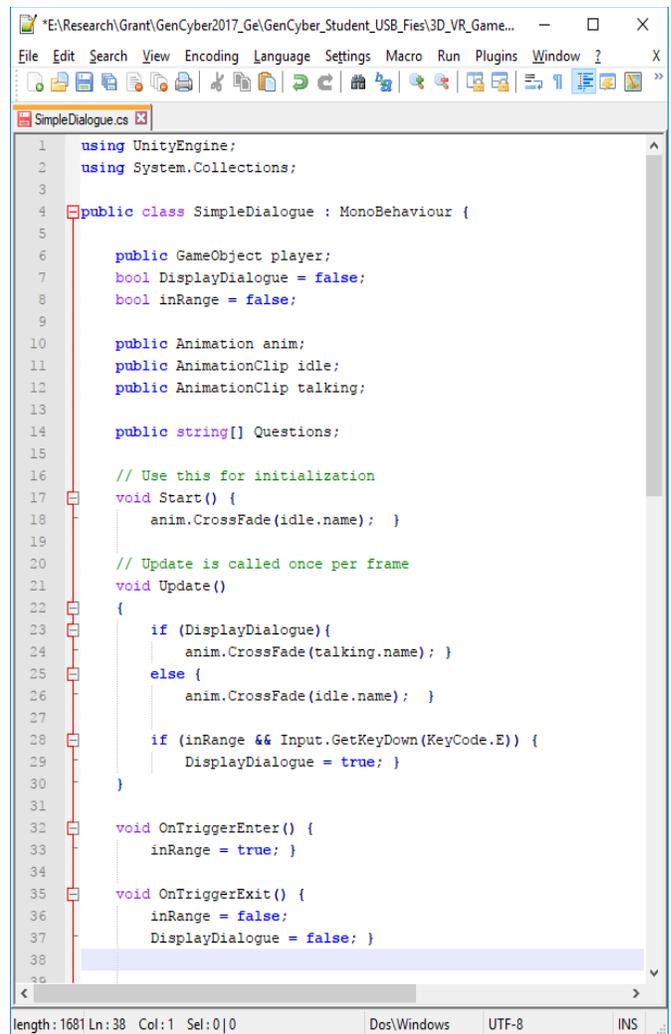


Figure 6. Unity C# Script to Trigger Talking Animation

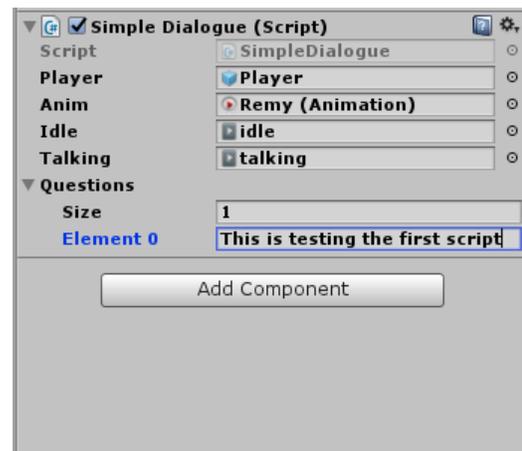


Figure 7. Simple Dialogue Script Interface to Set a Number of Public Variables



Figure 8. 3D Example of a Social Engineering Game Screen

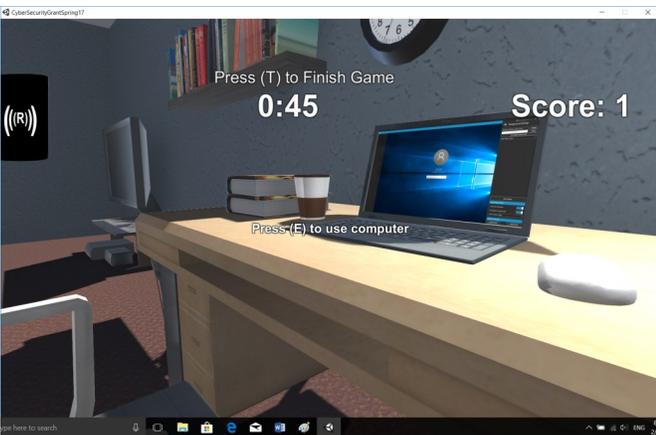


Figure 9. Example of a 3D Secure Online Behavior Game Screen

## Development of a Cyber Defense Tower Game in Unity3D

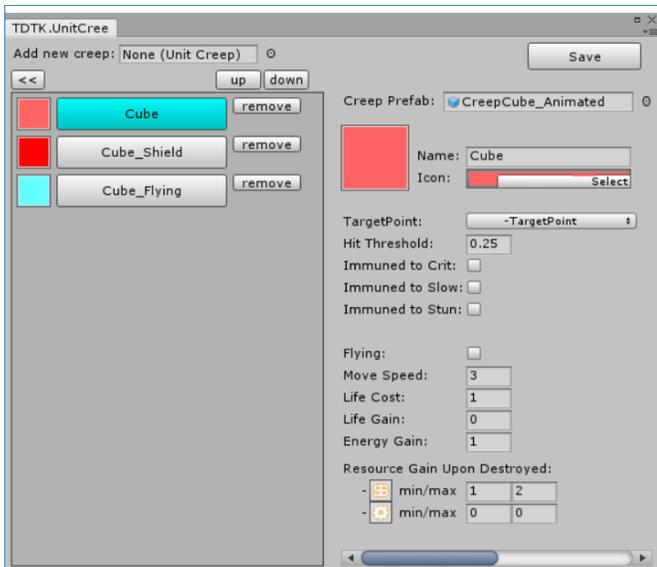
The Tower Defense Toolkit (TDTK) developed by Song Tan is a Unity C# script library that allows game developers to quickly create Tower Defense prototype games [15]. The Cyber Defense Tower game was implemented on top of this TDTK framework and includes custom-designed models and art assets. Users can also integrate their own art assets to make their own unique Tower Defense game. Seven unique cyber-attacks (see Figure 10) and six cyber defense towers (see Figure 11) are included. One limitation of TDTK is that there are only two types of attacks—ground and air (see Figure 12)—and three types of defense towers: ground, air, and hybrid (see Figure 13). It is impossible to use the built-in attacks and defense towers to simulate cyber-attacks and defenses. In order to solve this issue, the Tower Defense Toolkit was customized to include seven additional attack types, including Virus, Phishing, Trojan, Spyware, Ransomware, DDoS, and Sniffer (see Figure 14), and six additional defense towers, including Antivirus, Password, System Update, Secure Cyber Behavior, Encryption, and Firewall (see Figure 15). Some defense towers will defend a single type of attack, while other defense towers can defend multiple attack types. For example, the Antivirus tower will defend against Virus, Trojan, and Spyware attacks. In addition, multiple defense towers can be used together, such as implementing the Password and Encryption towers against a Sniffer attack. The Cyber Defense Tower Game contains three difficulty levels: tutorial, intermediate, and competition. Figure 16 shows the tutorial level and Figure 17 shows the competition level to demonstrate the different levels of complexity.



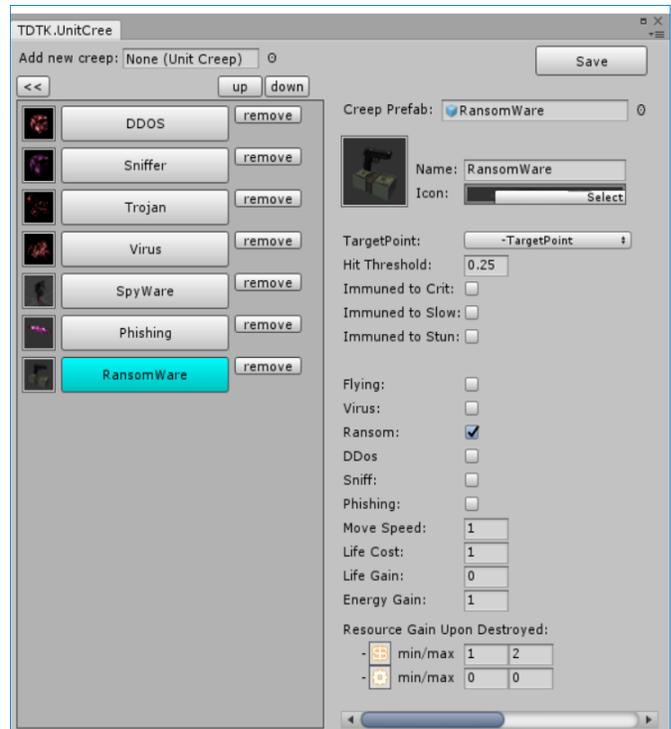
Figure 10. Types of Cyber-Attacks in the Cyber Defense Tower Game



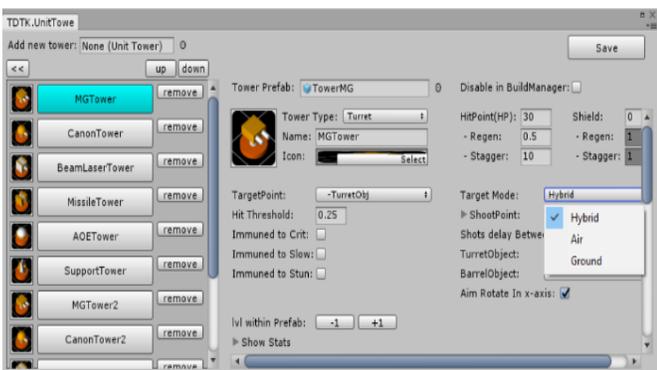
Figure 11. Types of Cyber Defenses in the Cyber Defense Tower Game



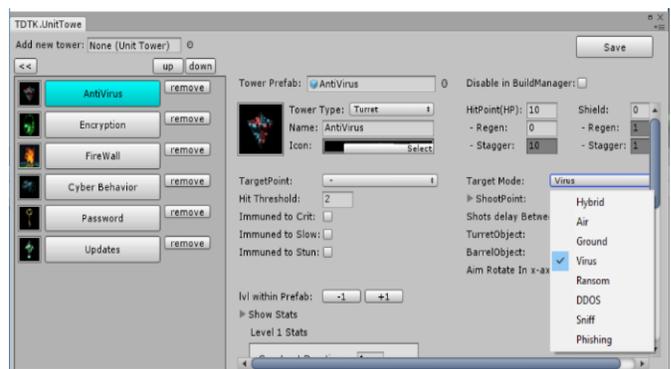
**Figure 12. Two Types of Attacks in the Original Tower Defense Toolkit**



**Figure 14. Additional Seven Cyber Attacks in the Cyber Tower Defense Game**



**Figure 13. Three Types of Defense Towers in the Original Tower Defense Toolkit**



**Figure 15. Six New Cyber Defense Towers in the Cyber Tower Defense Game**

## Single-Player GenCyber Card Game

The original GenCyber card game was designed and created by Dr. Vincent Nestler at California State University at San Bernardino [14]. The single-player adaptation of the GenCyber Card game was developed in the Processing programming environment to enhance student understanding of ten cybersecurity First Principles (see Figure 18). The site team observed GenCyber camp participants playing the game during their down time, and some students were even creating cheat sheets so they could beat their friends' times. Table 1 compares the four cybersecurity education games developed in this study. The technical features of each game were compared based on game genres, dimension of the game world, the game development engine, 3D character modeling, 3D character animation, and game scripting.

## Results and Discussion

Purdue University Northwest successfully launched two one-week summer camps in June of 2016 and two additional one-week camps in June of 2017. A total of 181 high school students attended the PNW GenCyber summer camps, with 107 of these from underrepresented minority populations as identified by the NSF report on "Women, Minorities, and Persons with Disabilities in Science and Engineering: 2017" [16] (see Table 2).

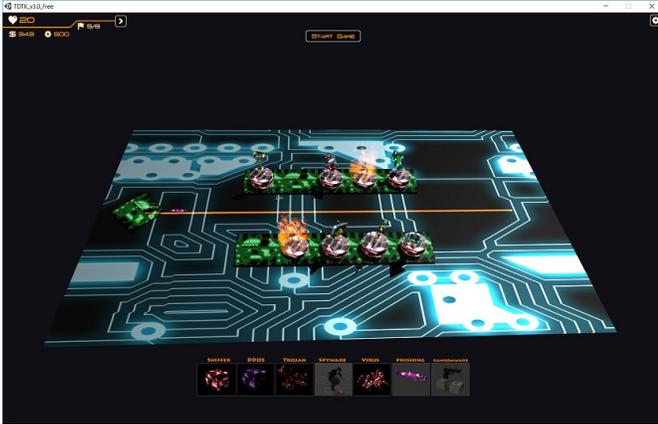


Figure 16. Tutorial Level in the Cyber Tower Defense Game



Figure 17. Competition Level in the Cyber Tower Defense Game

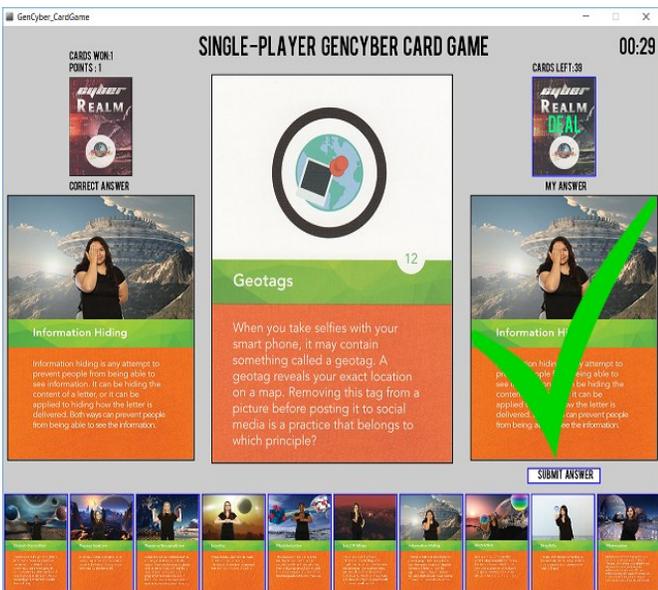


Figure 18. Single-Player GenCyber Card Game

Table 1. Comparison of Four Cybersecurity Games

	Social Engineering	Secure Online Behavior	Cyber Defense Tower	GenCyber Card Game
Game Genre	Role-Playing	Role-Playing	Tower-Defense	Card-Game
Game Dimension	3D	3D	3D	2D
Game Engine	Unity3D	Unity3D	Unity3D	Processing
Character Modeling	Required	Required	Not Required	Not Required
Character Animation	Required	Required	Not Required	Not Required
Game Scripting	C# script	C# script	C# script	Processing

Table 2. Demographic Information of PNW GenCyber Camp Participants

Year	Gender	Number of participants	Race	Number of participants
2016	Male	60	Caucasian	34
	Female	26	Non-Caucasian	52
2017	Male	63	Caucasian	40
	Female	32	Non-Caucasian	55
Total		181		181

During the one-week summer camp, each student participated in activities mentored by a team of PNW faculty members and student assistants. At the opening ceremony of the summer camp, the VR social engineering game was presented in the CAVE virtual environment. After the opening ceremony, camp participants played this 3D social engineering game at their own pace in order to learn the concept of social engineering and become familiar with 3D game control. Once the students got used to the game controls and were exposed to the other games, they competed against one another for prizes and to promote a sense of fun and excitement in the classroom. After competing in groups of twenty-five students in each of the games—3D Secure Online Behavior, Cyber Defense Tower, and Single-player GenCyber Card Games—one winner was picked from each competition and was awarded with a small gift on the last day of the summer camp.

The post-camp survey was conducted at the last day of the summer camp. A 5-point Likert scale was used to measure the students' satisfaction with camp activities and experiences ranging from 5 (strongly agree) to 1 (strongly disagree). The post-camp survey had 154 respondents (see Table 3).

**Table 3. Demographic Information of PNW GenCyber Post-Camp Survey Participants**

Year	Gender	Numer of participants	Race	Numer of participants
2016	Male	50	Caucasian	30
	Female	22	Non-Caucasian	42
2017	Male	57	Caucasian	34
	Female	25	Non-Caucasian	48
Total		154		154

Survey participants indicated that game-based learning for cybersecurity enhanced knowledge in cybersecurity, understanding of the cybersecurity first principles, and general security awareness (see Table 4). The activities and games also motivated students to pursue higher education and careers in the field of cybersecurity. The mean scores of male and female students, as well as the difference in rating scores between various ethnic groups, indicated that there could be gender and racial difference in the participants' evaluation of the game-based cybersecurity education method. Hypothesis testing for two population means with unequal variance (T-test) was used to test gender and racial differences for each survey question. For each survey question, both two-tail and one-tail hypothesis tests were performed. For example, the hypothesis for "Q1. I enjoyed learning about computer science" was:

- Two-tail hypothesis test:  
 H0: There is no difference in mean survey rating of Q1 between female and male students ( $\mu_1 = \mu_2$ ).  
 HA: There is a difference in mean survey rating of Q1 between female and male students ( $\mu_1 \neq \mu_2$ ).  
 Significance level ( $\alpha$ ) = 0.05
- One-tail hypothesis test:  
 H0: The mean survey rating of female students is higher than or equal to male students ( $\mu_1 \geq \mu_2$ ).  
 HA: The mean survey rating of female students is lower than for male students ( $\mu_1 < \mu_2$ ).  
 Significance level ( $\alpha$ ) = 0.05

**Table 4. Post-Camp Survey Questions and Results**

Question	Post-Camp Survey Questions	Rating
Q1.	I enjoyed learning about computer science.	4.36
Q2.	I would like to learn more about computer science.	4.22
Q3.	I enjoyed learning about cybersecurity.	4.27
Q4.	I would like to learn more about cybersecurity.	4.05
Q5.	The teachers/faculty in this program made me more interested in cybersecurity	4.20
Q6.	I know what cybersecurity means.	4.27
Q7.	I know more about cybersecurity than I did before this camp.	4.36
Q8.	I know more about computer science than I did before this camp.	4.26
Q9.	I am more comfortable learning cybersecurity concepts now.	4.08
Q10.	I know more about information security than I did before this camp.	4.29
Q11.	I can explain why cybersecurity is important.	4.18
Q12.	Overall this camp was a good experience.	4.46
Q13.	I am glad I attended this camp.	4.46
Q14.	I would like to attend more camps like this.	4.17
Q15.	My opinions and ideas were respected in this camp.	4.32
Q16.	I found the camp activities interesting.	4.22
Q17.	I liked interacting with the teachers at this camp.	4.28

The results of hypothesis testing show that there were significant differences between the male and female students' impressions about the camp activities in survey question 1 and survey question 16. The one-tail hypothesis test indicates that the male students rated survey questions 3, 5, and 11 higher than did the female students (see Table 5). These results can be interpreted as indicating that male students found the game-based learning camp activities more enjoyable and interesting than did the female students. To test differences among ethnic groups, both two-tail and one-tail hypothesis tests were performed for Caucasian and non-Caucasian participants. The hypothesis for "Q1. I enjoyed learning about computer science" was:

- Two-tail hypothesis test:  
 H0: There is no difference in mean survey rating of Q1 between Caucasian and non-Caucasian students ( $\mu_1 = \mu_2$ ).  
 HA: There is difference in mean survey rating of Q1 between Caucasian and non-Caucasian students ( $\mu_1 \neq \mu_2$ ).  
 Significance level ( $\alpha$ ) = 0.05

2. One-tail hypothesis test  
 H0: The mean survey rating of non-Caucasian students is higher than or equal to the Caucasian students ( $\mu_1 \geq \mu_2$ ).  
 HA: The mean survey rating of non-Caucasian students is lower than for Caucasian students ( $\mu_1 < \mu_2$ ).  
 Significance level ( $\alpha$ )= 0.05

**Table 5. Evaluation of Gender Differences in Game-Based Learning for Cybersecurity Education**

Quest #	Mean Female Rating (n = 47)	Mean Male Rating (n = 107)	p-value (two-tail test)	p-value (one-tail test)
Q1.	4.0851	4.4766	0.0072	0.0036
Q2.	4.0000	4.3178	0.0973	0.0486
Q3.	4.0638	4.3551	0.0903	0.0452
Q4.	3.9362	4.0935	0.4241	0.2121
Q5.	3.9787	4.2991	0.0587	0.0294
Q6.	4.1915	4.3084	0.4596	0.2298
Q7.	4.3191	4.3832	0.7309	0.3654
Q8.	4.1489	4.3084	0.4471	0.2235
Q9.	3.9149	4.1509	0.2053	0.1027
Q10.	4.2128	4.3178	0.5111	0.2556
Q11.	3.9574	4.2804	0.0745	0.0373
Q12.	4.3913	4.4951	0.4637	0.2319
Q13.	4.3043	4.5243	0.1899	0.0950
Q14.	4.0000	4.2524	0.2075	0.1037
Q15.	4.3043	4.3204	0.9125	0.4563
Q16.	3.9130	4.3592	0.0120	0.0060
Q17.	4.1957	4.3107	0.5073	0.2536

The results of hypothesis testing between ethnic groups show that there are no significant differences between Caucasian and non-Caucasian students regarding the camp activities and experiences. However, the one-tail hypothesis test indicates that the Caucasian students rated survey question 11 higher than non-Caucasian students (see Table 6). This result shows that the Caucasian students have higher overall self-efficacy than non-Caucasian students do after the game-based learning camp activities. Professors Zheng Yan and Melissa Dark conducted independent evaluations of GenCyber camp with support from the NSF EAGER grant, “Developing Cybersecurity Judgment Questionnaire for GenCyber Campers.” All PNW camp participants were encouraged to participate in the quiz-style independent evaluation. However, due to the nature of the anonymous study,

the authors could not obtain the performance data from the PNW camp. Beginning in 2018, PNW summer camps will offer a knowledge assessment quiz both before and after the game-based learning sessions in order to further enhance understanding of student knowledge attainment.

**Table 6. Evaluation of the Racial Differences in Game-Based Learning for Cybersecurity Education**

Quest #	Caucasian Rating (n = 64)	Non-Caucasian Rating (n = 90)	p-value (two-tail test)	p-value (one-tail test)
Q1.	4.4063	4.3222	0.5007	0.2503
Q2.	4.2500	4.2000	0.7555	0.3777
Q3.	4.3594	4.2000	0.2573	0.1287
Q4.	4.1406	3.9778	0.3238	0.1619
Q5.	4.2188	4.1889	0.8393	0.4196
Q6.	4.3594	4.2111	0.2897	0.1448
Q7.	4.3594	4.3667	0.9639	0.4820
Q8.	4.1250	4.3556	0.1903	0.0951
Q9.	4.1429	4.0333	0.4924	0.2462
Q10.	4.2969	4.2778	0.9005	0.4502
Q11.	4.3438	4.0667	0.0694	0.0347
Q12.	4.5238	4.4186	0.3855	0.1928
Q13.	4.5397	4.3953	0.2745	0.1372
Q14.	4.2857	4.0930	0.2412	0.1206
Q15.	4.2857	4.3372	0.7344	0.3672
Q16.	4.2857	4.1744	0.4375	0.2187
Q17.	4.3016	4.2558	0.7724	0.3862

## Conclusions

In this paper, the authors introduced an innovative game-based learning method for cybersecurity education. Four computer games were developed to educate social engineering and information security concepts, secure online behaviors, and cybersecurity first principles. These games provided an excellent platform for assisting high school students in learning these important concepts, as well as to differentiate between secure and insecure online behaviors. This approach is beneficial to the future cybersecurity workforce as it exposes more high school students to cybersecurity as a career pathway at a time when they are making decisions regarding higher education. The game-based learning method was well received by the students, support staff, instructors, and site visit team. This was also supported by the post-camp survey conducted with 154 participants, with average

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ratings of 4.26 out of 5 on all Likert-based responses. To investigate the gender and ethnic differences among participants, hypothesis testing for two population means with unequal variance (T-test) was conducted with the survey data. The hypothesis testing results indicated that male students overall thought that the game-based learning activities were more enjoyable and interesting than female students, and that Caucasian students showed slightly higher self-efficacy with cybersecurity concepts than non-Caucasian students after the game-based learning camp activities.

## Acknowledgements

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# DEVELOPMENT OF A SOLAR THERMAL WATER MANAGEMENT SYSTEM AS AN UNDERGRADUATE RESEARCH EXPERIENCE

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## Abstract

To reduce the negative impact of energy usage on the environment and the cost of using fossil fuels, people are encouraged to use the available sources of renewable energies, in particular solar energy. Being able to collect and use solar energy, however, requires solar collectors. The two types of solar collectors available are non-concentrating (or flat-plate type) and concentrating (or focusing-type). For the non-concentrating type, the collector area that intercepts the solar radiation is the same as the absorber area, while in concentrating collectors, the area intercepting the solar radiation is much greater than the absorber area. Concentrating collectors are more efficient than the non-concentrating and can provide higher temperatures. The main objective of this senior project was to develop solutions to harness the solar energy and use it to develop an efficient residential solar thermal water management system. The authors believe that this system will make life easier for mankind and save the environment.

## Introduction

The development of the solar thermal water management system (STWMS) [1] was highly influenced by the direction of the country, which is to advance energy conservation through renewable energy opportunities. Residential applications of solar water heaters have the potential to replace expensive electrical and gas water heaters that generally costly to operate. Universities, especially engineering education departments, are incorporating initiatives to back the government in its strategic plan of energy independence by motivating students to use their engineering knowledge to formulate ideas and machinery that can be used to excel in the productivity of the proposed system. In engineering education, the use of high-tech equipment is the most beneficial feature for formulating concepts for new innovations. Students engage in process modeling, testing and simulation, and data acquisition and process control. Virtual applications enhance both theoretical and hands-on knowledge of engineering technology students by supporting laboratory experiences. There has been an immense amount of research and development on behalf of the engineering technology

seniors at TTU in the simulation of the STWMS. The main goal of the project was to construct an energy-independent system capable of continually replenishing itself by creating a solar collector box that is cost effective, efficient, and environmentally friendly. The design focused on the need for use of renewable resources and the need to reduce electricity costs in Tennessee households. The design promotes the use of solar water heating systems in homes. The project was also used to promote the use of green development and solar technology.

## Research Approach

Brainstorming was conducted and ideas were shared among team members and the project advisor in order to determine the best configuration for the system. The project helped build on an already well-rounded education by enabling each team member to learn how to execute an in-depth research analysis and acquire project-management skills by starting with a conceptual idea and finding factual information and resources to make the idea a reality. The project also helped emphasize the fundamental importance of teamwork, because team members were able to learn new things from one another, which gave the project a practical-engineering atmosphere.

In this paper, the authors discuss: 1) the benefits of using the STWMS; 2) the energy transfer principles and how they can be used for solar thermal systems; 3) the composition of the system, along with functionalities of its operations; 4) the details regarding the control system of the STWMS and an explanation of how the system is linked together; 5) a comparison of the STWMS with today's standard water heaters and their energy-efficiency data; and, 6) development of a prototype of the STWMS through manufacturing and system assembly/integration to bring ideas into reality for feasible measures to the cost of production.

## Benefits of the Study

Renewable energy alternatives have multiple benefits for their users; the STWMS has three main benefits, including environmental gains, economical profit, and energy produc-

tion. The system would benefit the environment simply because it does not run completely on electricity or any other type of fuel; therefore, it does not emit any harmful byproducts. The STWMS is basically pollutant free. In the long run, the system would help reduce the amount of pollutants released into the air, which would not only benefit the environment but would help improve the health of humans, due to the fact that we would be breathing cleaner air. The economic benefits of the system would not necessarily be evident at first. The consumer would have upfront investment costs for the purchase of the STWMS; but, in the end, that consumer would receive a payback through the money saved on monthly utility bills. The amount of money saved would correlate with the system's efficiency, which would basically depend on what region of the country the consumer lived in and how much sunlight that region received.

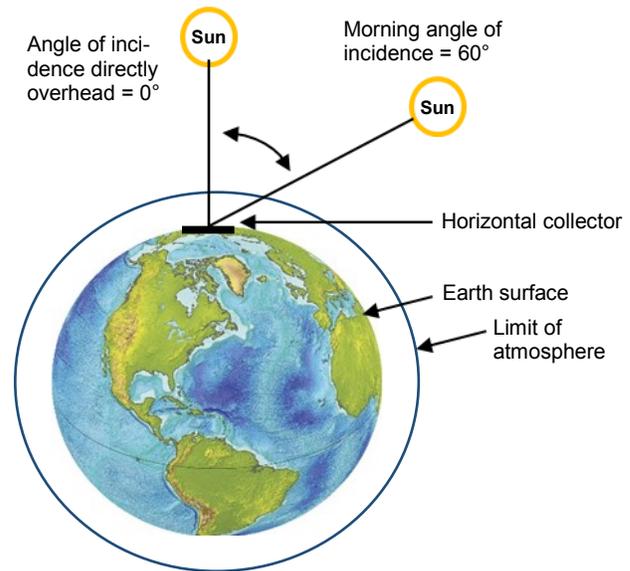
Lastly, the STWMS would benefit the energy production of any household or business that utilizes it. A more realistic indicator of the performance of the solar thermal water heater would be its daily energy output from its collectors. Based on a typical solar thermal water heater, the output contributes typically 7-10 kilowatt-hours per day, depending on the solar resources and the type of collector being used. Whereas a typical residential electric water heating system consumes about 12-14 kilowatt-hours per day, depending on the temperature of the groundwater that enters the system. As can be seen, there are multiple benefits of the solar thermal water management system. The abundance of savings is reason enough for consumers to want to purchase and install the system into their existing water heating system for significant cost reductions.

## Energy Transfer Study

The three main basics of heat transfer are conduction, convection, and/or radiation [2]. Conduction is the transfer of thermal energy from one object to another through direct contact, where the heat moves from the hotter object to the colder object. In this transfer, the amount of heat transferred is proportional to the area of contact and the temperature difference. Convection is the heat transfer from one place to another by the movement of fluids. The amount of heat transferred by convection is affected by the area of contact, the temperature difference, and the amount of constraint on the movement of the fluid, such as its viscosity. Radiation transfer of heat energy is by electromagnetic radiation. Radiation operates independently of the medium through which it occurs and depends upon the relative temperatures, geometric arrangements, and surface structure of the materials that are emitting or absorbing the heat.

## Solar Radiation at the Earth's Surface

Solar radiation is energy emitted by the sun reaching the earth's surface, which cannot be turned on or off (see Figure 1). To understand the theory of this solar energy system, how much energy is available from the sun must be found and how this amount of energy is divided by day and year. Accordingly, average solar radiation produces 1.35 kWh of energy per square meter of surface that is directly facing the sun above the earth's atmosphere. Radiation travels directly from the sun to the earth without being scattered or diffused then radiation has been scattered as it travels through the atmosphere. The effect that radiation has on the earth's atmosphere is the inability for meteorologists to predict the amount of radiation that will reach the earth's surface, due to radiation being scattered and absorbed by air, water evaporation, dust, smoke, and smog.



**Figure 1. Solar Radiation Emitted to the Earth's Surface**

The sun moves from east to west through the sky throughout the day, but moves on a different path as the earth's tilt changes relative to the position of the sun throughout the year. The declination is the angular position of the sun at solar noon with respect to the plane of the equator, which is demonstrated by Cooper's equation—see Equation (1) [3]:

$$\delta = 23.45^\circ \sin \left( 2\pi \frac{284 + n}{365} \right) = 23.45^\circ \sin \left( 2\pi \frac{284 + 122}{365} \right) = 15.21^\circ \quad (1)$$

where,  $n = \text{days} = 122$  (May 2<sup>nd</sup>, 2014) and  $\delta = \text{declination}$ .

The solar hour angle is one of the most important factors involving heat energy. When the solar angle declines or inclines, it changes the thermal energy of the sun's radiation. At solar noon, the hour angle is 0.000 degrees, with the time before solar noon expressed as negative degrees and the local time after solar noon expressed as positive degrees. For example, the hour angle when the sun rises in the morning in Cookeville, Tennessee, is  $-100.24^\circ$  (May 2<sup>nd</sup>, 2014) from the hour angles equation of Equation (2) [3]:

$$\cos(\omega_s) = -\tan(\psi) \cdot \tan(\delta) \quad (2)$$

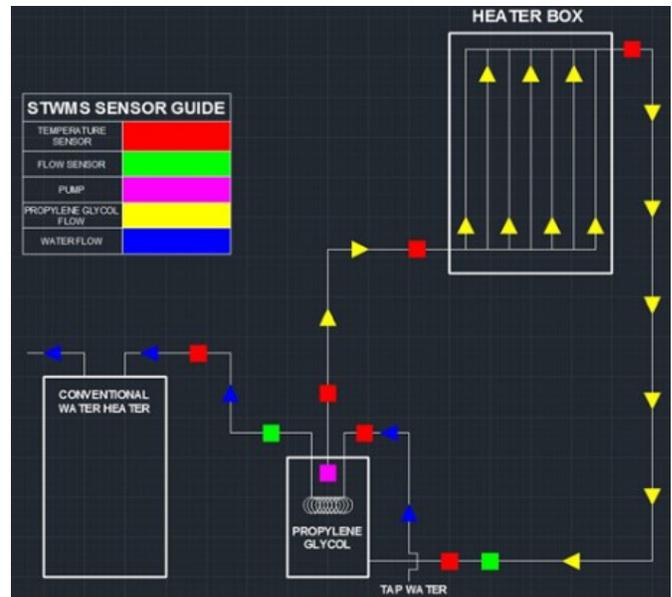
where,  $\omega_s$  is hour angle;  $\psi$  is latitude; and,  $\delta$  is declination.

The angle closest to  $0^\circ$  will attain more sun radiation and the angle further from  $0^\circ$  will have a reduced amount of sun radiation relative to the origin of the surface of the solar collector. Therefore, the best collector tilt depends on the particular application in which sun is required throughout the year. The end product has the potential to become the most economical and efficient system to be used in households, due to the application of convection and radiation within the collector box and convection application within the storage tank, where the fluids act as a heat exchanger [4-6]. In addition, the product has the potential to reduce household energy consumption in states such as Tennessee.

Average electricity consumption for Tennessee households is 33% higher than the national average and among the highest in the nation [7-9]. The electric water heater consumes about 18% of the total household energy. Compared to other areas of the U.S., the warmer weather in Tennessee and its neighboring states means that air conditioning accounts for a smaller portion of home energy use (10%), while space heating accounts for a larger portion (34%) [10].

## STWMS Description

Figure 2 shows the schematic CAD drawing for system assembly. The STWMS is a hybrid solar water heating system. As the name implies, it combines two or more heat sources—electrical heat generation together with solar preheating of the incoming city water. The hybrid system provides a high level of energy savings. The improved functionality allows the system to have automated features to run solely on solar energy during moderately hot days of the year, and as a joint operation of solar and electrical power to generate hot water during mild weather. The significance of this configuration results from an effective method of utilizing renewable energy, because the sun is the most powerful resource known to mankind.



**Figure 2. STWMS Plumbing/Electrical Schematic**

The first component of the hybrid system involves the solar aspect of powering the system. In order to generate and retain the power from the sun, sun radiation is extracted and stored in order to heat the water. The design of the solar collector box in this study for absorbing incident solar radiation was selected by combining two of the four solar collector boxes commonly used in industry. The integration of the flat-plate collector and the parabolic trough provides benefits from both concepts. The flat-plate collector theme allows heat radiation to be collected and trapped within the dimensions of the box, in order to preserve collected heat. Solar radiation is captured in the collector box and focused at any point along parabolic curves, where it is then reflected towards the copper pipes containing propylene glycol. Glycol is used to store the radiation then used to preheat the water. After being heated, the glycol is sent to a storage tank where it acts as a heat exchanger. An additional copper pipe is connected to the tap water outlet, which passes through the glycol tank in which the water is heated and sent to the water heater storage tank, similar to a conventional heating system.

The second component of the hybrid system involves an alternate power input to the system through the electric power supply. This aspect of the system is automated by converting power between solar or electrical power. The functionality of the automated system is based on a thermostat reading that is interconnected to a control system that reads the weather conditions for operations. The electrical power can be provided by local utility companies then connected to the STWMS for power supply alternatives to heating the water.

## Raspberry Pi Data Microcontroller/Data Acquisition

Figure 3 show the Raspberry Pi microprocessor interface to the STWMS. The Raspberry Pi is used to connect all of the temperature sensors for data acquisition and control; it is a low-cost, credit-card-size computer that plugs into a computer monitor or TV and uses a standard keyboard and mouse. A simple python code is used to configure temperature sensors. The Raspberry Pi is responsible for automatically collecting liquid flow and temperature data. The processor also has the ability to turn the glycol pump on and off, depending on weather conditions and time of day.

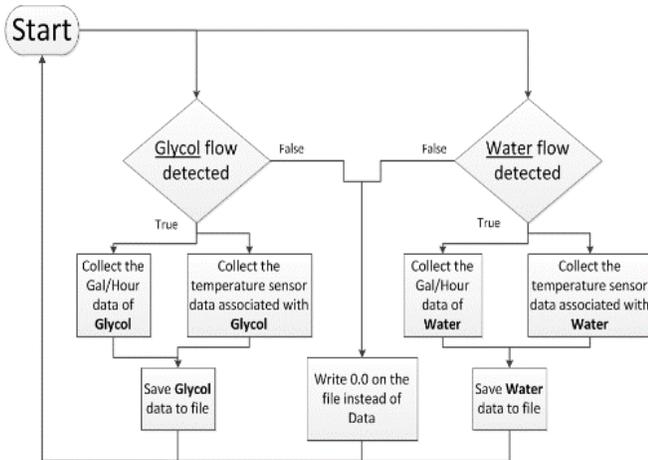


Figure 3. Raspberry Pi Programming Flowchart

If the glycol is flowing through the collector box, the system collects data and writes it to the file. If glycol is not flowing through the system, the program writes a zero, indicating that there is no flow. The same applies to the flow of water through the system. The system behavior contains processes that transform inputs into outputs (material, energy, or data). Data collection is stored into Excel spreadsheets for analytical analysis of the hot water produced, solar input, and the time of regulation hybrid durations. A flow meter is also incorporated into the Raspberry Pi controller, with temperature gauge readings to measure how hot the water becomes.

## STWMS Output Study

The standard metric unit for measuring heat energy is Joules (J). The formula for obtaining energy transfer is given in Equation (3):

$$\Delta Q = M \cdot C_p \cdot \Delta T \quad (3)$$

where,  $Q$  is the quantity of energy transfer;  $M$  is equal to the mass of substance per kg;  $C_p$  (in kJ/kg°C) is the specific heat capacity of the substance; and,  $\Delta T$  (in °C) is the amount of temperature difference in the substance [11, 12].

Since this is an indirect system, the lowest temperature would be the minimum room temperature of 63°F (~17°C), and the target temperature would be 125°F (63°C). One liter of water is 1 kg and the specific heat of water ( $C_p$ ) is 4.19 J/kg°C. So the energy needed to raise the temperature of one gallon of water (3.78 kg) from 63°C to 17°C ( $\Delta T = 46^\circ\text{C}$ ) is equal ~720 kJ. Since the required energy and efficiency have various factors to be considered, another similar formula is used in order to make comparisons. The energy,  $E$ , required to raise the temperature of one liter by 1°C is 4.19 kJ. Assuming that the capacity of the system is  $C$  liters, and the temperature of the water is raised by  $T^\circ\text{C}$ , the energy required is given by Equation (4):

$$E = (4.189 \cdot C \cdot \Delta T) \text{ kJ} \quad (4)$$

Using the same assumptions:

$$E = 4.19 \text{ kJ/kg}^\circ\text{C} \cdot 75 \text{ kg} \cdot (125^\circ\text{C} - 63^\circ\text{C}) = 97,417.5 \text{ kJ}$$

Assumptions were also made for the determination of the solar collector area and angle of inclination:

- Heat required per day = 97,417.5 kJ
- Solar energy radiation on the inclined surface of the collector is:  
(6199 x 60 x 60) kJ/m<sup>2</sup>/day = 20,055 kJ/m<sup>2</sup>/day
- The minimum collector box efficiency is assumed to be 40%
- Collector box area = (energy required/energy available efficiency)  
(97,417.5 / 20,055 · 0.4) m<sup>2</sup>
- The slope of the collector,  $\beta$ , and the angle of inclination,  $\delta$ , are calculated using Equations (5) and (6), respectively:

$$\delta = 23.45 \sin [0.9863 (284 + n)] \quad (5)$$

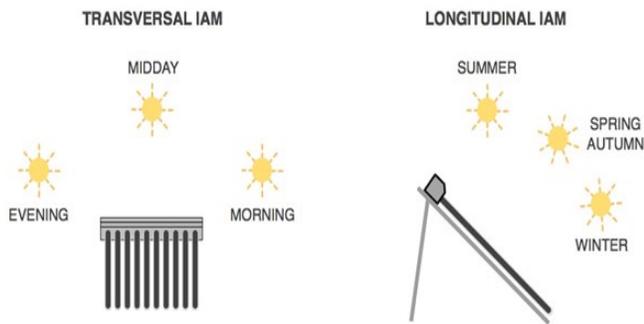
where, for May,  $n = 15$  and  $\delta = -21.27$ .

$$\beta = (Q - \delta) \quad (6)$$

where,  $Q$  is the latitude at the test site and equal to 36°, 9N.

$$\beta = [36.9 - (-21.27)] = 58.17^\circ$$

Figure 4 shows how the collector ideally should face south at an angle of ~58°.



**Figure 4. Slope and Direction of the Sun Collector**

The angle of the collector relative to the sun is crucial for maximizing the efficiency of the solar collector box. The output from the solar collector box changes as the angle between the collector box changes and the more surface area the copper pipes have.

## Solar Collector Fabrication

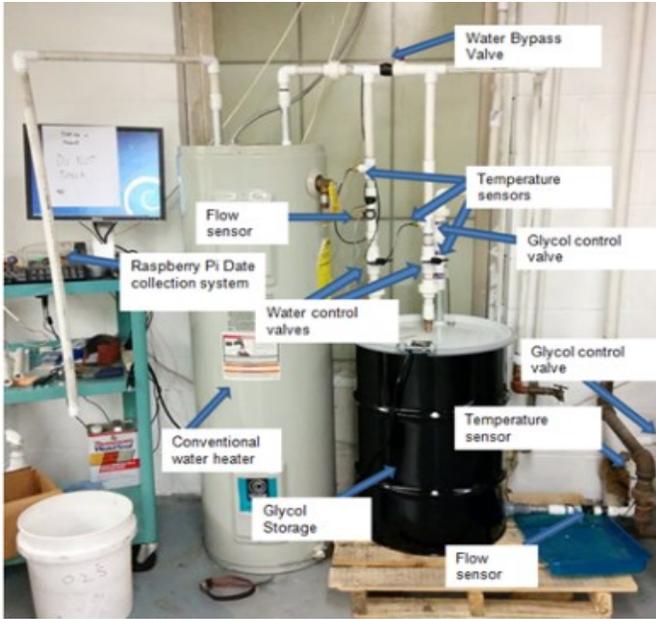
Figure 5 shows the steps used for building the solar collector. For the frame, a 4'x6' base of the collector box frame was made from plywood and reinforced by pieces of 2'x8' treated pine wood to create the side walls for the frame. Styrofoam was placed inside the collector box for purposes of insulation, support, and a water-tight seal. All sides of the box and the base of the frame were lined with the installation material in order to ensure that no heat got inside the box. PVC piping was then split in half and seven of the cut outs were placed in a linear array inside the collector box in order to create a parabolic layout. The PVC piping was then lined with Mylar to create a reflective surface by measuring and tailoring the Mylar to the contours of the PVC piping. Finally, an adhesive spray was used so that the Mylar could bond to the PVC piping.

A CNC machine was used to cut out positioning supports, which were responsible for holding the copper piping at the center of the parabolic focal point. The next involved soldering copper coils into the copper pipes, which would be used to bring water into the system and distribute it out for storage or usage. The copper assembly was then placed into the pipe support slits and the copper runner bars positioned inside the inlet and outlet cutouts. The solar collector box had a single glaze acrylic to insulate the pipes from the outside environment, and a rubber weather seal was installed around the perimeter of the box to further insulate the box. The last step involved coating the frame of the collector box with high-heat thermal spray paint in order to attract more heat to the structure and absorb it into the system. The thermal paint helps in maximizing heat through radiation entrapment and containment.



**Figure 5. Steps used to fabricate the Solar Collector**

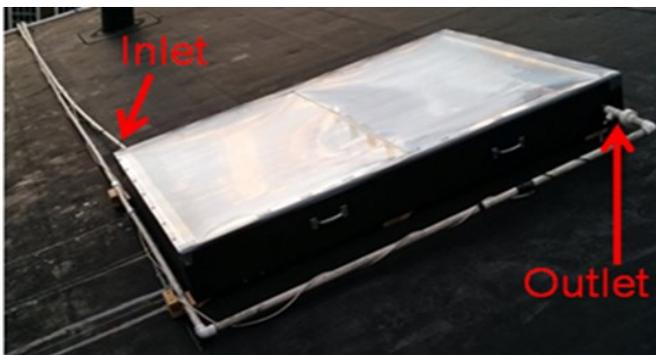
The solar collector array was set at a 40° angle on the top of the lab's inclined roof facing south in order for the parabolic surface to have maximum exposure to direct sunlight. The box was stationary, without any permanent connection to the roof, due to the high coefficient of friction between the rubber roof and the wooden support brackets at the base of the structure. Figure 6 shows how the inlet and outlet pipes allow glycol to be circulated in a continuous loop so that the ground water can be pre-heated before being stored in the conventional water heater for use.



**Figure 6. The Solar Collector Box Mounted On the Roof of the Laboratory**

## Complete STWMS Assembly

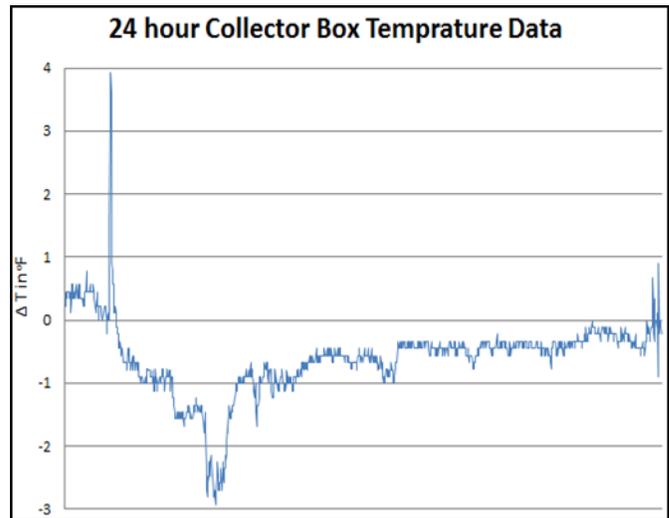
Figure 7 shows an assembled STWMS. Also shown in this figure is a 30-gallon electric water heater and black glycol storage drum that constantly circulates fluid through the sun collector box on top of the building to be heated and stored in the drum with a heat exchanger for preheating water before it goes to the electric water heating system. The system uses a sump pump to circulate the glycol solution within the solar collector and storage drum. Flow sensors and temperature sensors were installed on the city water side of the system as well as the inlet and outlet values for the glycol. Also, Raspberry Pi data collection is shown with all of the sensors connected for data acquisition and control of the system.



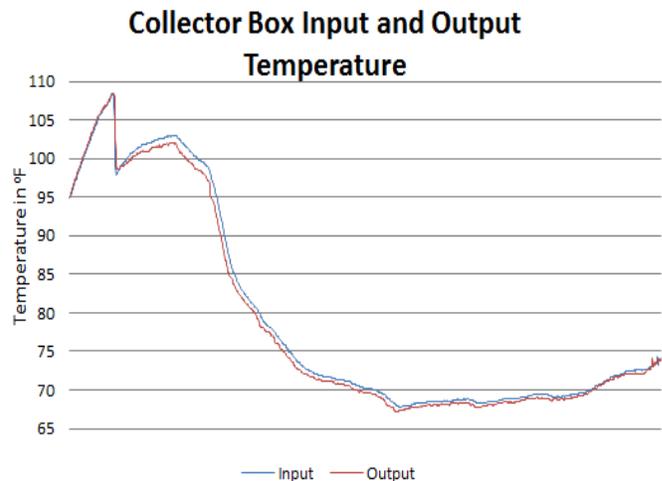
**Figure 7. The Assembled STWMS Installed Inside the Laboratory**

## Preliminary Test Results

Figures 8 and 9 show preliminary data collected from the solar water heater in the month of April, 2014. Several system improvements were made in order to maintain the temperature inside the box during winter. The improvement included the use of double-glazed covers and vacuum-tube solar collector. The system was able to heat 10 gallons of water from an initial temperature of 94°F to a final temperature of 106°F before more water was added in the glycol storage drum and before adverse weather conditions caused a drop in temperature. Overall, system performance met the authors' expectations. However, more testing is required during clear weather.



**Figure 8. Temperature Data For the 24-hour Solar Collector Box**



**Figure 9. Input and Output Temperature Data for the Solar Collector Box**

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## Conclusions and Lessons Learned

The proposal for designing this project revolved around alternative solutions for improving current household electrical water heater energy efficiency. Our senior project's team found that using solar energy would be the best solution for this problem, simply because the energy from the sun is free, once you pay for the initial cost of such a solar thermal water management system (STWMS). The anticipated payback for the STWMS was ~7 years for the Tennessee region, while reducing negative impacts on the environment and reducing U.S. dependency of foreign oil. The simple payback will be more expedient in the warmer states like Florida and South Carolina, where the payback period could be 2-3 years. During the period of this study, the research team was able to: 1) learn about solar energy and how it is used in the world today; 2) learn new skills in manufacturing processes like welding and plasma cutting; 3) explore new ideas and concepts to produce the final product; 4) learn more about product design from concepts to development; 5) use critical-thinking skills to find solutions for technical problems; and, 6) use the project-management and teamwork skills learned to overcome problems faced during this process and meeting the project's deadlines.

## Acknowledgements

The work for this project was supported by the Department of Manufacturing and Engineering Technology at Tennessee Tech University. A warm welcome is extended for the contributions by the MET Department, COE, and TTU for providing the necessary machinery, books, and computers needed to build the STWMS. A special thanks also to Dr. Ahmed Elsayw for his help, advice, and innovation for discovering solutions for renewable energy utilization, and for sharing his wealth of knowledge on the theory on solar energy. Many thanks to our classmates who helped in this project for the diligence they displayed in their research, designing, and implementation.

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# MODELING THE BEHAVIOR OF RETAINING WALLS IN ORGANIC SOILS

Behnam Maki Abadi

## Abstract

The retaining wall is a structure whose main purpose is to prevent lateral movement, retain ground or water, and possibly act as a factor for vertical load bearing. Slope wall stabilization is one of the important issues in geotechnical engineering. Therefore, the aim of this current study was to complete a previous study and model the investigation of the behavior of retaining walls for unsuitable soils for construction. PLAXIS software was used to model the behavior of the retaining walls. The results showed most displacement was observed when all layers were composed of organic soil. The most movements occurred in cases where the soil was modeled in an organic layer in the lower layer, where the organic soil was at the highest level, and also where the organic soil was in the middle layer. Also, the shear force input to the retaining wall was higher when the structure had the organic soil in the highest layer, and the lowest shear force was applied to the retaining wall when the structure had the organic soil at its lowest layer. The comparisons showed that the highest stress occurred when the organic soil was designed in the middle layer. This indicates that, in the case where the organic soil is in the middle layer, more stress is tolerated by the entire system and there is less displacement.

## Introduction

In recent years, due to the development of cities and the increase in population, the number of underground floors and depth of excavation have increased. Slope wall stabilization is one of the important issues in geotechnical engineering [1, 2]. The retaining wall is a structure whose main purpose is to prevent lateral movement, retain ground or water, and possibly act as a factor for vertical load bearing. One of the most important concerns in the civil-geotechnical field is the protection of excavation and existing adjacent buildings. Without such protections, and if not followed by suitable methods for protecting the conveyances and the slopes under construction, irreparable damages can occur. The risks created because of possible settlement, reduction in load capacity, and changes in lateral locations can cause cracks in adjacent structures [3]. There are several types of retaining walls, including axis retaining walls, tin walls, and backfill walls. Concrete's back surface is reinforced through contact operations [4]. The foundation skele-

ton acts as a permanent support and prevents slipping. This type of concrete foundation retaining wall is widely used, because of its simple construction and cost efficiency [5].

Since soil has no tensile strength and is sensitive to atmospheric factors such as weathering, trench stability is very important. The necessity of implementing a retaining wall in urban construction is controlled by the engineering organization [6]. Design and implementation of an underground retaining wall is necessary. Usually, builders have negative attitudes toward retaining wall and believe that their implementation is costly and difficult. For this reason, in many projects, even with two or three underground floors, it can be seen that the retaining wall is not designed. There are different methods for solving problems caused by earth loads, such as building stone retaining walls, concrete retaining walls, and geogrid retaining walls [7]. Since geogrid walls have many advantages compared to other walls, it can withstand the earth pressure and afford a rise in the base level of the building. According to code 2800, the base level of a building can be calculated from the base level of the retaining wall, where the retaining wall has been implemented around the structure and does not have any breaks. The base level has an effect on the calculation of seismic earthquakes; that is, a rise in the base level affects the reduction of the seismic coefficient [8].

Because of the importance of the subject, a lot of related studies have been done. Bagheri and Gosalipour [1] evaluated the performance of a retaining wall under seismic loads with different base levels of water behind the wall. Their results showed that the increase in the base level of the groundwater in the structure depended on the amount of stress in the wall. Also, an increase in the base level of groundwater in the structure leads to an increase in a displacement of 5-13%, which can seriously affect the performance of the wall [1]. Another study conducted by Akhlaghi et al. [9] compared the Mohr-Coloumb model with a hardening model using a method of bored piles for slope wall stabilization. The results clearly showed that the hardening model had more realistic results compared to the Mohr-Coloumb model. In another study, Chavan and Sharma [10] investigated possible reasons for the breaking of a retaining wall in the city of Hyderabad, India, using the geotechnical numerical code, FLAC3D. The results showed that the cracking was broadly distributed and also that the thickness of the reinforced concrete wall affected this distri-

bution. To achieve find other reasons for breaks in the concrete, a numerical analysis using the geotechnical numerical code, FLAC3D, was used by Chavan and Sharma [10]. In other research, the results of an investigation into the behavior of mechanically stable earth (MSE) walls for differential shrinkage showed that the cost, friction angle, BACKFILL, geogrid tensile strength, reinforcement length, and the height of the MSE wall had notable effects on the geosynthetic horizontal and vertical movements and pressure [7]. In this current study, the authors aimed to complete a previous study with the aim of modeling and investigating the behavior of retaining walls for unsuitable soils for construction.

## Methodology

In this study, numerical methods were used to analyze the environment of soil and diaphragm walls. The two-dimensional PLAXIS was used to demonstrate the possibility of analyzing and modeling the proposed idea. The finite element method and different models were used to analyze the environment of the soil, as well as the stress and strain caused by changing environments.

## The Parameters of the Design

The parameters of the design included the characteristics of the soil, geometric values, partial coefficients, reliability, and loading specifications. These parameters were defined at the beginning of the optimization process and remained constant during the process. Problem design constraints were broken down into two categories: behavioral and geometric. The behavioral constraint depends on the behavior of the concrete retaining wall against input pressure. These constraints are defined in the form of modulus of rupture using Equation (1):

$$G_i(x) \leq 0 \quad i=1, \dots, 10 \quad (1)$$

where,  $x$  denotes the vector of variables of the design.

Table 1 shows the behavioral constraints of the problem. Behavioral constraints are, in fact, the limits of the rules that must be followed. So, it is necessary to first calculate the pressure of soil. This calculation is performed in the active mode according to the type of problem and the input parameter, according to the Coulomb or Rankine equation. The main purpose of the retaining wall is to withstand the vertical and lateral pressures from the soil. The vertical pressure of the soil is determined from the product of the specific weight of the soil at its height, which is simple to calculate when the specific weight is known. The lateral pressure of the soil at each point along the height of the soil is deter-

mined from the product of the weight of the soil column ( $\gamma H$ ) at the coefficient of the lateral pressure of the soil ( $K$ ).

**Table 1. Behavioral Constraints of the Problem**

Modulus of rupture	Unequal constraints	Modulus of rupture	Unequal constraints
Shear capacity of blade	$G_1(x)$	$G_6(x)$	Bearing capacity
Flexural capacity of blade	$G_2(x)$	$G_7(x)$	Shear capacity of toe
Topple stability	$G_3(x)$	$G_8(x)$	Flexural capacity of toe
Slip stability	$G_4(x)$	$G_9(x)$	Shear capacity of footing
No traction at the foundation	$G_5(x)$	$G_{10}(x)$	Flexural capacity of footing

## Design of Weight Retaining Walls for Earthquake Conditions

In the lateral soil pressure (impulsive and resistant) on retaining walls, taking into consideration the earthquake force, the retaining walls can tolerate limited displacement, even during an earthquake. Its design, based on Richards, is a method for designing weight retaining walls in which a limited amount of lateral displacement is allowed. In this method, the inertial forces of the wall are also considered, and the adhesion of the embankment is assumed to be zero, as given by Equation (2):

$$w_w = \left[ \frac{1}{2} H^2 (1 - k_v) \right] C_{IE} \quad (2)$$

where,  $y_l$  is the specific weight of embankment.

The lateral pressure of the soil and the retaining wall are calculated using Equation (3):

$$C_{IE} = \frac{\sin(\beta - \delta) - \cos(\beta - \delta) \tan \varnothing_2}{(1 - k_v)(\tan \varnothing_2 - \tan \theta')}$$

$$\theta' = \tan^{-1} \left( \frac{k_h}{1 - k_v} \right) \quad (3)$$

To determine the weight  $w_w$ , an acceptable position change is used, where the tolerable displacement of the wall,  $\Delta$ , is selected. The value of  $k_h$  of the design is deter-

mined using Equation (4) (Das, 2009) and structural elements include: 1) plates and shells; 2) anchors; 3) a geogrid; and, 4) a common level.

$$k_h = A_a \left( \frac{0.51 A_v^2}{A_a \Delta} \right)^2 \quad (4)$$

The input parameters of the plates include flexural strength, given by Equation (5):

$$EI = E \cdot \frac{h^3 \cdot b}{12} \quad (b = 1\text{ m}) \quad (5)$$

Normal hardness, given by Equation (6):

$$EA = E \cdot h \cdot b \quad (b = 1\text{ m}) \quad (6)$$

Element thickness, given by Equation (7):

$$d = h = \sqrt{12} \cdot \frac{EI}{EA} \quad (7)$$

And plate weight, given by Equation (8):

$$W = (y_{concrete} - y_{soil}) \cdot d_{real} \quad (8)$$

## Mohr-Coulomb Model

In this study, the Mohr-Coulomb elastic-plastic model was used to model the slip. This model includes five input parameters:  $\nu$  and  $E$  for soil elasticity;  $\phi$  and  $c$  for soil plasticization; and,  $\psi$  for the soil dilation angle. The Mohr-Coulomb model shows a first-order approximation of rock or soil behavior. It is suggested that this model be used for an initial analysis of the problem. For each layer, a constant average hardness is guessed. Due to this constant average hardness, the calculations are relatively fast, and a basic image of deformations can be found. The initial soil horizontal stresses should be created by choosing the correct  $K$  values (Zoo et al., 2014).

## Formulation

The Mohr-Coulomb yield criterion is the generalization of the Coulomb friction law to the general states of stress. The Mohr-Coulomb yield criterion, when formulated based on the main stresses, consists of the yield functions given in Equations (9)-(14):

$$f_{1a} = \frac{1}{2}(\sigma_2' - \sigma_3') + \frac{1}{2}(\sigma_2' + \sigma_3') \sin \varphi - c \cos \varphi \leq \varphi \quad (9)$$

$$f_{1b} = \frac{1}{2}(\sigma_3' - \sigma_2') + \frac{1}{2}(\sigma_3' + \sigma_2') \sin \varphi - c \cos \varphi \leq \varphi \quad (10)$$

$$f_{2a} = \frac{1}{2}(\sigma_3' - \sigma_1') + \frac{1}{2}(\sigma_3' + \sigma_1') \sin \varphi - c \cos \varphi \leq \varphi \quad (11)$$

$$f_{2b} = \frac{1}{2}(\sigma_1' - \sigma_3') + \frac{1}{2}(\sigma_1' + \sigma_3') \sin \varphi - c \cos \varphi \leq \varphi \quad (12)$$

$$f_{3a} = \frac{1}{2}(\sigma_1' - \sigma_2') + \frac{1}{2}(\sigma_1' + \sigma_2') \sin \varphi - c \cos \varphi \leq \varphi \quad (13)$$

$$f_{3b} = \frac{1}{2}(\sigma_2' - \sigma_1') + \frac{1}{2}(\sigma_2' + \sigma_1') \sin \varphi - c \cos \varphi \leq \varphi \quad (14)$$

The yield equations are a function of the internal friction angle of the soil and adhesion and together form a hexagonal pyramid in the space of the main stresses. In addition to the yield functions, six potential functions—shown in Equations (15)-(20)—are also defined for the Mohr-Coulomb model:

$$g_{1a} = \frac{1}{2}(\sigma_2' - \sigma_3') + \frac{1}{2}(\sigma_2' + \sigma_3') \sin \Psi \quad (15)$$

$$g_{1b} = \frac{1}{2}(\sigma_3' - \sigma_2') + \frac{1}{2}(\sigma_3' + \sigma_2') \sin \Psi \quad (16)$$

$$g_{2a} = \frac{1}{2}(\sigma_3' - \sigma_1') + \frac{1}{2}(\sigma_3' + \sigma_1') \sin \Psi \quad (17)$$

$$g_{2b} = \frac{1}{2}(\sigma_1' - \sigma_3') + \frac{1}{2}(\sigma_1' + \sigma_3') \sin \Psi \quad (18)$$

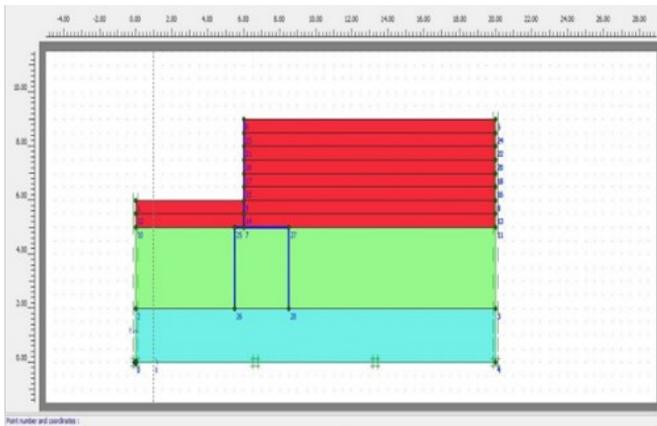
$$g_{3a} = \frac{1}{2}(\sigma_1' - \sigma_2') + \frac{1}{2}(\sigma_1' + \sigma_2') \sin \Psi \quad (19)$$

$$g_{3b} = \frac{1}{2}(\sigma_2' - \sigma_1') + \frac{1}{2}(\sigma_2' + \sigma_1') \sin \Psi \quad (20)$$

In these equations,  $\psi$  represents the potential functions of the dilation angle. This parameter is needed to model the changes of positive strain of the soil (dilation), especially in dense sandy soils. PLAXIS uses the Young model as the main hardness modulus in the Mohr-Coulomb model. Selectable hardness modulus values require a lot of accuracy for the calculations, as most soils exhibit nonlinear behavior at the beginning of loading. In geotechnical problems, for areas with a large linear elastic range, the use of the initial slope  $E_0$  is closer to reality, but for cases of loading, the load factor modulus is typically used at 50% resistance, or  $E_{50}$ . In issues such as tunneling and excavation,  $E_{ur}$  must also be used.

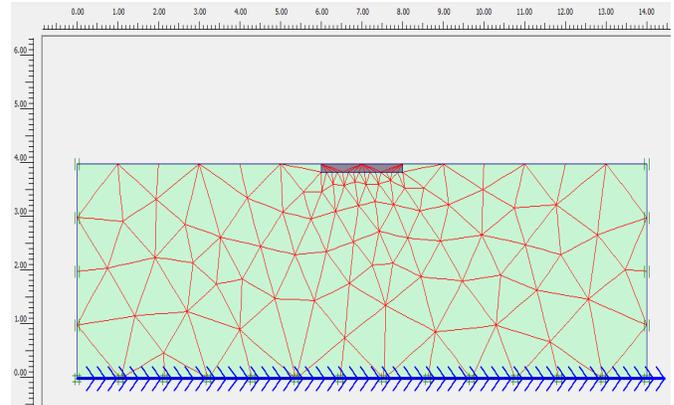
## Discussion and Modeling Results

The first scenario was modeled and the upper soil layer located on the back and front of the retaining structure was considered as organic soil. Figure 1 shows how this retaining structure model was created as a plain-strain model with 15 nodes.

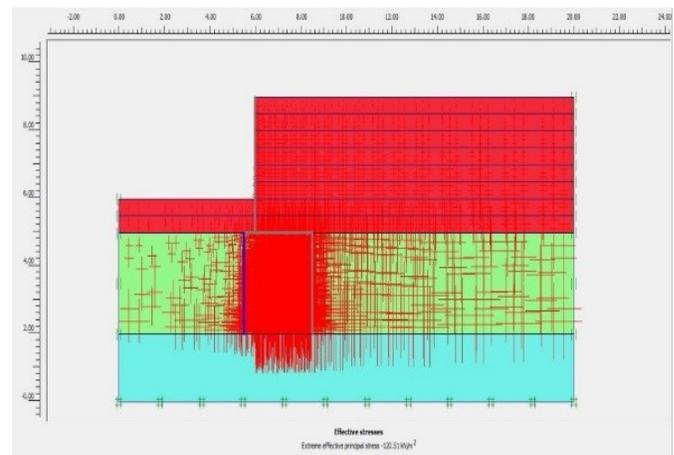


**Figure 1. The Model Created in PLAXIS 2D Software**

The Load menu and the Standard Fixities option were used to set the boundary conditions. At this stage, the model has been meshed. It is worth mentioning that the more the mesh weaves tightens or loosens, the accuracy of the analysis increases and the speed of analysis is reduced. Therefore, determination of the mesh size depends on the engineering judgment and should be selected appropriately so that the accuracy of the work is suitable and increasing the analysis time will not be a problem. To do this, the Mesh menu is used. Figure 2 shows a model of the mesh. In the next step, the exterior pressure conditions are defined according to the coefficient  $K_0$  for the model. The most effective stress is introduced into the model at the end. Figure 3 shows the value obtained from the software, which was equal to  $-120.51 \text{ kN/m}^2$ .



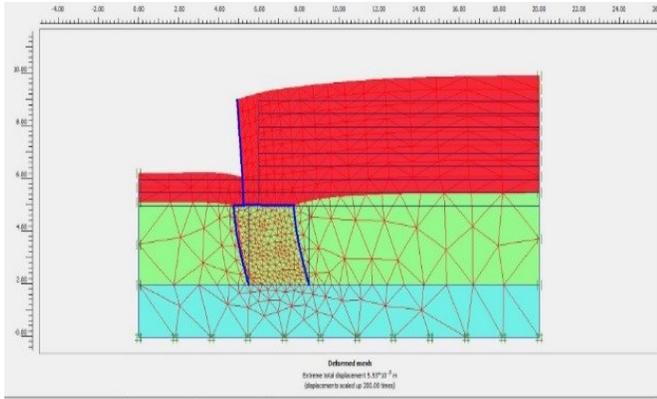
**Figure 2. Meshing of the Models Used in the Current Study**



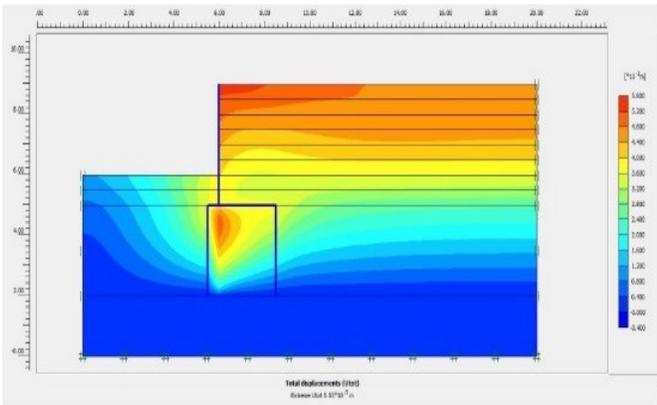
**Figure 3. Effective Stress Entered into the Model in the Initial Conditions for the First Scenario**

## The Output of the Software in the First Scenario

After the phasing of the model, the results of the output of the software showed that the amount of settlement in the first scenario was equal to  $5.53 \times 10^{-3} \text{ m}$ . Figure 4 shows the organic soil in the first layer and the back and front of the retaining structure. The results also showed that the maximum stress in the first scenario, that the soil of the first layer is the organic one, was equal to  $-139.39 \text{ kN/m}^2$ . The results of survey of the maximum displacement in the first scenario showed that the maximum effective input stress was equal to  $-139.39 \text{ kN/m}^2$ . Figure 5 shows that the organic layer was in the first layer. The input bending moment to the retaining wall in the first scenario was  $67.74 \text{ kN/m}$ . The horizontal displacement entered into the retaining wall was  $5.38 \times 10^{-3} \text{ m}$  for the simulations of the first scenario. The shear force entered to the retaining wall in the first scenario was  $46.27 \text{ kN/m}$ .



**Figure 4. Settlement in the First Scenario**



**Figure 5. Maximum Displacements in the First Scenario**

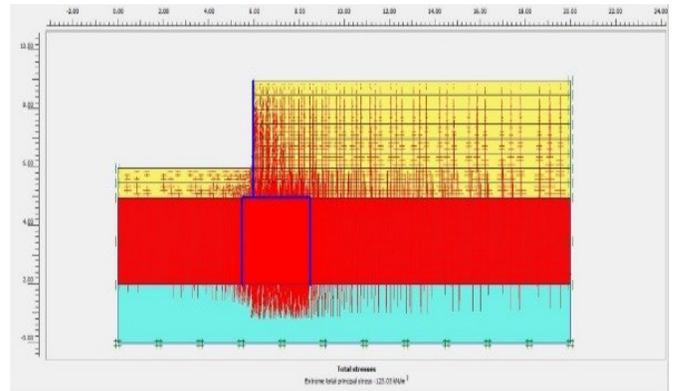
### The Output of the Software in the Second Scenario

The results obtained from the software in the second scenario showed that the amount of settlement in the second scenario was  $4.40 \times 10^{-3} \text{ m}$  and that the organic soil was in the second layer. Figure 6 shows that the maximum stress in the second scenario, where the soil of the second layer is organic, was  $-123.03 \text{ kN/m}^2$ . The results showed that the maximum displacement in the second scenario was  $4.40 \times 10^{-3} \text{ m}$ . The input bending moment into the retaining wall in the second scenario was  $40.87 \text{ kN/m}$  and that the organic soil was in the middle layer. Also, the shear force entered for the simulation of the retaining wall in the second scenario was  $31.46 \text{ kN/m}$ .

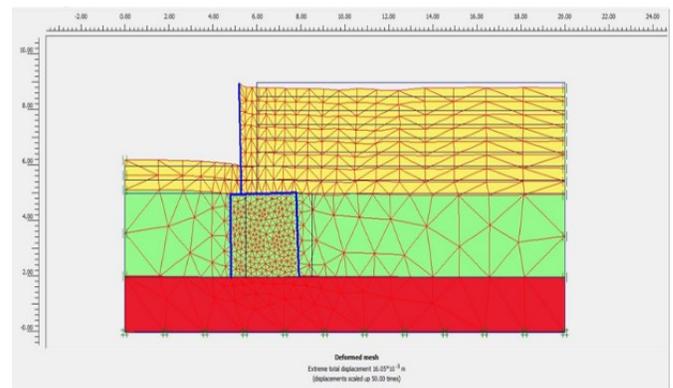
### The Output of the Software in the Third Scenario

From Figure 7, where the lower layer was modeled as organic soil and where the organic matter was located in the

third layer, the results obtained from the software in the third scenario indicate that the amount of settlement was  $10.05 \times 10^{-3} \text{ m}$ .



**Figure 6. The Maximum Stress in the Second Scenario**



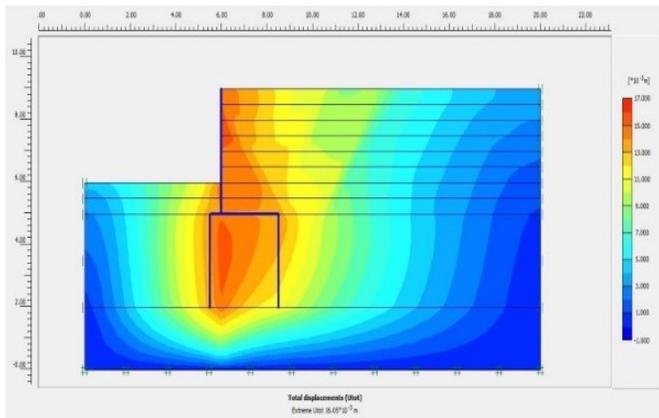
**Figure 7. Settlement in the Third Scenario**

The maximum stress in the third scenario, when the soil of the third layer was organic soil, was  $-157.94 \text{ kN/m}^2$ . Effective stress entered in the third scenario showed that the maximum effective stress, in the case where organic soil is in the lower layer, was  $-157.94 \text{ kN/m}^2$ . Figure 8 shows that the maximum displacement in the third scenario was  $16.05 \times 10^{-3} \text{ m}$ . The input bending moment to the retaining wall in the third scenario was  $33.29 \text{ kN/m}$ , when the organic soil was in the lowest layer and at the end of model. The horizontal displacement entered into the retaining wall was  $16.05 \times 10^{-3} \text{ m}$  in the simulations in the third scenario. The shear force entered into the simulation for the retaining wall in the third scenario was  $20.85 \text{ kN/m}$ .

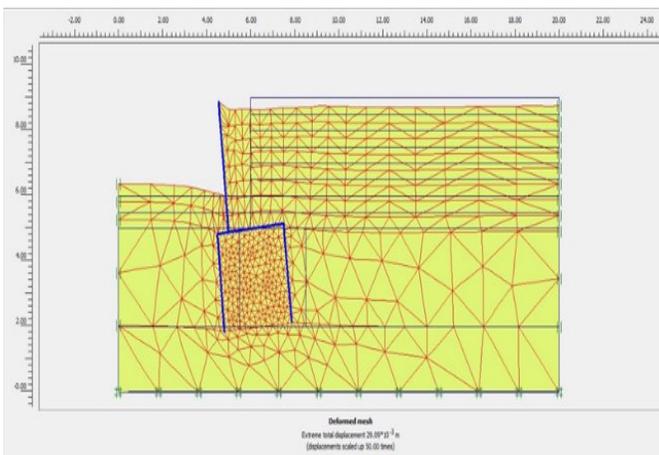
### The Output of the Software in the Fourth Scenario

Figure 9 shows that the results obtained from the software for the fourth scenario, where the entire amount of settle-

ment for all layers was modeled as organic soil, was  $29.09 \times 10^{-3} \text{m}$ .



**Figure 8. Maximum Displacement in the Third Scenario**



**Figure 9. Settlement in the Fourth Scenario**

The maximum stress in the fourth scenario, when the soil of all layers was organic soil, was  $-145.80 \text{ kN/m}^2$ . Effective stress entered in the fourth scenario was  $-145.80 \text{ kN/m}^2$ . Also, the maximum displacement in the fourth scenario was  $20.09 \times 10^{-3} \text{m}$ . The input bending moment to the retaining wall in the fourth scenario was  $35.07 \text{ kN/m}$ , when the organic soil was designed to all model. The horizontal displacement entered into the retaining wall was  $29.00 \times 10^{-3} \text{m}$  in the simulations in the fourth scenario. The shear force entered to the retaining wall for the simulation of the fourth scenario was  $20.85 \text{ kN/m}$ .

## Conclusions

For this current study, where the modeling of the behavior of retaining walls in organic soils was conducted, the following results were obtained:

1. By comparing the displacement in four scenarios and existing models, it was concluded that the most displacement occurs when: 1) all layers are composed of organic soil; 2) when the soil is modeled as organic in the lower layer; 3) when organic soil is at the highest level; and, 4) when organic soil is in the middle layer.
2. By comparing the stresses in all of the models, it was concluded that the highest stresses were related to the state when the organic matter was in the middle layer. This suggests that, in the case of organic soil in the middle layer, more stress is tolerated by the entire system, in spite of having less displacement.
3. The shear force entered for the retaining wall was higher when the structure had an organic layer on the highest layer, and the amount of shear force on the retaining wall in the case where the structure had organic soil in the last layer was the least.
4. Examining the bending moment on the retaining wall, it was concluded that the highest amount of bending moment on the retaining wall occurred when the soil of the first and lower layers was organic; in this case, there was also the minimum amount of bending moment bending into the retaining wall. This suggests that the lower the layers containing organic soil, the less bending moment enters the wall.

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## Biography

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# SITE SELECTION USING MULTI-ATTRIBUTE DECISION ANALYSIS IN GIS: A CASE STUDY ON THE BROWNFIELDS OF MINNESOTA

Satpal Singh Wadhwa, North Dakota State University; Kambiz Farahmand, North Dakota State University; Lee Eunsu, New Jersey City University

## Abstract

Agriculture is a leading sector in the Midwest economy. Within it, grain production is especially important to natural resource-based economies in the upper Midwest. Distant proximity to export facilities, transportation is critical to product competitiveness in a global grain market. Much of the grain that is shipped in containers has to travel long distances to reach U.S. ports. Exporters are put at a competitive disadvantage when they are unable to obtain containers at a reasonable cost for their exports. This situation has increased the desire with inland shippers for more and closer availability of empty containers to facilitate grain transportation. The use of Greenfields for the development of these new depots is not prudent as there is already pressure to save productive agricultural lands and open spaces to advance sustainable development. This has highlighted the need to remediate and use Brownfield sites for any such commercial use of land. This should also support rejuvenating the physical environment, restoring the economies of urban areas, and reviving communities in towns and cities.

The objective of this research project was to prepare a comprehensive database of Brownfield sites and find the optimal locations among them in order to establish new container depots in the state of Minnesota. Geographic information systems (GIS) and multi-attribute weighted linear combination (WLC) based on weighted average are the tools used to conduct the analysis. The criteria that were used to select suitable sites are grain elevators, highways, railroads terminals, port terminals, and social and economic factors. The results of the study show that there are 90 Brownfield sites that are potentially feasible for the development of new empty-container depots in the state of Minnesota.

## Brownfields

The increased costs in the redevelopment of a site due to unknown or actual environmental pollution of land that is redundant, unexploited, or neglected within viable and industrial locations are known as Brownfields [1]. Brownfields are commonly linked to metropolitan locations that

were once industrialized and evacuated. A Brownfield can range from a small deserted filling station to a large steel mechanized operation. The locations total 77,502 acres, which is larger than St. Paul and the cities of Minneapolis combined. The definition of a Brownfield in certain instances may be the opposite of a Greenfield, which is a location reputed to be free from contagion and has not been previously utilized for industrial or commercial reasons. The pollution levels at Brownfield locations can vary from soil fragments to widespread contagion of ground water. The remediation costs of a Brownfield can be as little as a few thousand to millions of dollars, depending on the level of pollution and cleanup [2]. Brownfields have been in existence for many years. This has led to a Superfund program that was first launched in 1980 by the U.S. Congress to offer monetary aid for the overhaul of perilous locations. Additionally, the remediation sought to improve sites that pose risks in safety and public health as well as degrade the quality of the environment.

The U.S. Environmental Protection Agency (EPA) took charge of the Superfund program and a National Priority List (NPL) was created. All of the hazardous sites that needed widespread remediation were cataloged. The reformation of Brownfields was one of President Bush's main agenda items, which was reflected by allocation to the EPA of a budget of \$38 million in April of 2001 to enable ninety communities to clean up their lands [1]. Furthermore, the President also sanctioned a program that would help in decreasing the liabilities in the Superfund as well as increase funds on cleanup and appraisal called S 350. Despite these efforts, there are still about 500,000 polluted industrial and commercial sites, as stated by the U.S. Office of Government Accounting. It would be very beneficial for the country to have computer-based tools to help in the effective location, monitoring, and updating of records on Brownfield locations.

## Minnesota Brownfields

The characteristics of Brownfield properties exist in most parts of Minnesota, presenting an opportune time to improve the state's economy, reduce carbon emissions, better the environmental health, and free communities from their

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distress. There are about 425,000 Brownfields in the U.S (<https://portal.hud.gov/>). The metropolitan and industrial Brownfield locations in Minnesota are mostly found rural areas. Between 1995 and 2014, the Minnesota Pollution Control Agency (MPCA) listed more than 8000 Brownfields in the state that needed to be cleaned up. By September of 2014, more than 63,828 acres had been registered. Additionally, more than 13,674 acres were registered via the Petroleum Brownfields program. The locations total 77,502 acres, which is larger than St. Paul and the cities of Minneapolis combined.

## Benefits of Brownfield Cleanup and Redevelopment

The revitalization of the sites will bring about the following social, fiscal, and environmental benefits to the people living in the area.

1. Job Retention and Creation

The revitalization of Brownfields enables people in a community to obtain and retain jobs. For every \$10,000-\$13,000 invested in Brownfield recovery, one permanent job is created [3].

2. Tax Base Expansion and Revitalization

In more than 50 states, taxes totaling \$309 million were collected between 1993 and 2010 for Brownfield redevelopment [4]. The same study found that cities could collect at least \$872 million and as much as \$1.3 billion every year in tax revenues if Brownfields were revitalized in about 58 cities. Brownfield sites can be found within metropolitan locations; therefore, the magnitude of collectible taxes provides fiscal stimulus above what a single state or national grant could achieve.

3. Public Health Improvements

Places that have numerous Brownfields are faced with increasingly high threats to public health, due to exposure to low-quality air, harmful chemicals, high incidences of asthma, increased lead levels in blood, and a lack of recreation centers. Negative effects on health include death due to cancer and respiratory diseases. Therefore, the revitalization of Brownfields ensures improved health for neighboring communities.

4. Meeting Increasing Demand for Land Availability

The recovery of Brownfields is a way of saving land, especially Greenfield land, which is often habitable and suitable for agriculture. Brownfields offer an opportunity for the creation of a sustainable environment, as they are located close to canals, railways, and old roads, which makes them accessible and, thus, offers a locational advantage. The changes also help in the reduction of emissions and saving energy.

## Literature Review

### Geographical Information Systems and Multi-Criteria Decision Making

The purpose of integrating GIS and multi-criteria decision making (MCDM) is to gain the advantage of the synergy of these two discrete areas of research. GIS has a prominent role in spatial data visualization and analysis, while MCDM aids in knowledge-based decision making by assessing, evaluating, and ranking the alternatives [5-10]. GIS-based MCDM was used to design a tool for the park planning authorities in Calgary, Alberta [11]. The tool can support park management in informed decision making related to the need for improving existing parks and locating new public parks. Nine attributes were evaluated for measuring accessibility to these public parks. The research used the weighted linear combination of all attributes weighed, based on the number of residents living in an area.

GIS-based MCDM analysis was used to identify the areas that are prospects for the biochar application in agriculture in Poland [12]. The criteria used for analysis were soil pH, soil organic matter, soil texture, and contaminant loads. Maps were produced by overlaying these criteria spatially. The results of this study showed that 21.8% of the agricultural land in Poland has an intermediate potential for biochar. The synergy of GIS and MCDM can be used to design landfill-modeling procedures for the selection of landfill locations [13]. There are mainly three criteria that were used in order to evaluate suitable sites: environmental, social, and economic concerns. The use of multiple criteria offered significant potential improvements over the previous methods in terms of accuracy, criteria reliability, and criteria comprehensiveness. A research study was done by Fyodorova [14] to identify suitable Brownfields for installing medium (100-1000 kW) and large (1000-3000 kW) wind turbines. GIS and a multi-attribute weighted linear combination (WLC) method were the primary tools utilized to conduct the analysis. The criteria used to select suitable sites were: wind speed; historic landmarks; avian and wildlife habitat; conservation lands; and, proximity to airports, roads, and transmission lines.

### Analysis Methods

The most common methods used for locational analysis are Boolean overlay and WLC. Both methods “are often made up of combined approaches as none of the individual approaches provide a comprehensive method for wind energy site suitability analysis”. The Boolean method uses Bool-

ean operations such as intersection, difference, union, and others for the input layers. However, “Boolean searches are limiting because they provide only yes or no answers” [15]. On the contrary, the WLC method allows assigning weights according to the relative importance of each layer to the overall suitability measurement, and then combining the map layers to obtain an overall suitability score [16]. According to Rodman and Meentemeyer [17], this method is flexible and allows different inputs to be used to evaluate a variety of scenarios.

## Weighted Linear Combination Analysis

To identify the appropriate sites for the development of container depots in the study area, the WLC approach was used in this current study. Factors such as proximity to elevator clusters, proximity to railroad and port terminals, and social and economic factors were identified and used in the analysis. ArcGIS Spatial Analyst 10.4 was the primary tool used for data conversion and the WLC and overlay analyses. Figure 1 shows a flowchart of the complete process.

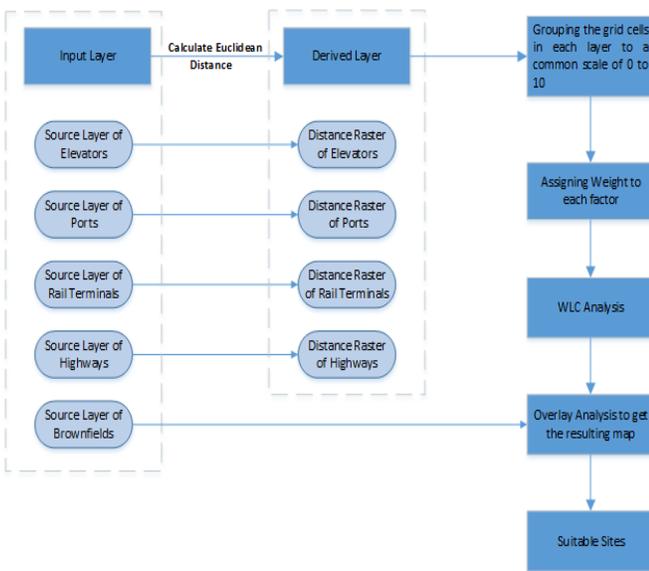


Figure 1. Flowchart for the WLC Analysis

## Data Collection

Based on the objectives of this study, the following criteria were developed that would cover most of the aspects and answer all of the research questions necessary for making a location decision (Brownfield selection) to open new depots. The data on the Brownfields were collected from the Minnesota Pollution Control Agency (MPCA) [18]. Table 1 lists the data format and source for each criterion.

Criteria 1: Grain elevators. The use of storage and transport capacity offered by grain elevators requires purposely designed container depots in close proximity to the location of the freight. The depots should be designed to be specific commodity; for example, in the case of grains, these should be designed as bulk terminals used to transport the grains to the desired destinations.

Table 1. Data Collection from Regulatory Sources

	Data Layer	Format	Source
Criteria	1. Grain elevators	Excel spreadsheets readable by ArcMap as .csv files and shapefiles	<a href="http://www.bnsf.com/">http://www.bnsf.com/</a>
	2. Port terminals, railroad terminals, and highways	Shapefiles	<a href="https://www.rita.dot.gov/">https://www.rita.dot.gov/</a>
	3. Property statistics (for social and economic actors)	Excel spreadsheets by ArcMap as .csv files and shapefiles	<a href="https://beacon.schneidercorp.com/">https://beacon.schneidercorp.com/</a>

Criteria 2: Proximity factor. The complexity of modern freight distribution over highways, railroads, and waterways is represented by the increased focus on intermodal and co-modal transportation solutions that appear to be the main causes of container capacity issues. This necessitates, then, a renewed focus on hinterland logistics. Congestion, energy consumption, and empty movements become the driving forces to consider before setting container depots near railroad terminals, which is the next step in freight planning.

Criteria 3: Property statistics. The online EPA database, Beacon, and qPublic.net are interactive public access portals that provide statistics on each property, such as tax parcel ID, area of the parcel, land use type, previous land use, business name, vacancy of the property, etc. Moreover, properties are further categorized based on contamination, with the highly hazardous sites (superfund) being eliminated from the analysis. Furthermore, in order to develop container storage depots for sites with a given area, a minimum size of 15 acres is needed. Now, the vacancy status of the property can be searched using property tax information and can be added as another new field in ArcMap. Table 2 shows the different fields of the data that were added for each potential site. Also considered was the fact that the site (property) chosen for setting up of new depots would be at a safe distance from the population of the nearest city.

**Table 2. Fields for Each Potential Site**

Site Number	Field
1	Business Name
2	Street Address
3	Area in Acreage
4	Land use Type
5	Status

## Methodology

To begin the analysis, all of the data were converted to the same projection; that is, all of the data were stored in NAD27 Minnesota Project Zones in Central State Plane. The data acquired from other sources were stored in different projections and were projected to NAD27 Minnesota Project Zones in Central State Plane in order to keep the projection format consistent. The next step was to prepare data for the WLC analysis by converting them into a raster format and then reclassifying the grid cells in each raster layer into ten classes and assigning scores to the classes (see Table 3). The reclassify tool allowed grouping of the grid cells on each layer into ten classes and assigning a score to each class on a scale of 0-10, with 0 being the least suitable and 10 being the most suitable. The Euclidean was used for conversion because it creates the range of distances (buffer zones) that are calculated from the center of the objects of interest (layer features such as roads and landmark features), while converting vector layers to raster format. The distances were calculated using a Euclidean algorithm. The maximum distance was set to 25,000 meters to consider only grid cells within 25,000 meters from objects of interest as candidates.

Grid cells outside of the threshold distance of 25,000 meters were assigned to a 'NoData' category at the output. After road data were converted to the grid format, all other layers were set to the same extent as the road raster layer before being converted to raster format, because it had the largest extent. It should be noted that 'NoData' cells were assigned zero values, because the process of overlaying 'no value' cells with cells containing numerical values would result in a 'no value' grid of cells in the output layer. Finally, the weighted overlay tool was used to conduct the WLC analysis. During this analysis, each reclassified dataset was multiplied by its associated weight and then all weighted raster layers were combined to produce a composite raster map showing a final suitability score for each grid cell. Table 4 shows what weight percentage was assigned to each

criterion. The weight represents the relative importance of each layer and can be modified when the criteria importance changes. The importance of each layer was based on personal judgment.

**Table 3. Classes and Suitability Score of Criteria**

	Class	Score		Class	Score
Layer 1. Grain Elevators	0 - 200m	1	Layer 4. Port Terminals	0 - 3000m	1
	200 - 400m	2		3000 - 4000m	2
	400 - 1000m	3		4000 - 5000m	3
	1000 - 2000m	4		5000 - 6000m	4
	2000 - 3000m	5		6000 - 7000m	5
	3000 - 4000m	6		7000 - 8000m	6
	4000 - 5000m	7		8000 - 9000m	7
	5000 - 6000m	8		9000 - 10000m	8
	6000 - 7000m	9		10000 - 11000m	9
	7000 - 10000m	10		11000 - 12000m	10
	>10000m	0		>12000m	0
No Data	0	No Data	0		
Layer 2. Rail Road Terminals	0 - 3000m	1	Layer 5. Highways	0 - 200m	1
	3000 - 4000m	2		200 - 400m	2
	4000 - 5000m	3		400 - 1000m	3
	5000 - 6000m	4		1000 - 2000m	4
	6000 - 7000m	5		2000 - 3000m	5
	7000 - 8000m	6		3000 - 4000m	6
	8000 - 9000m	7		4000 - 5000m	7
	9000 - 10000m	8		5000 - 6000m	8
	10000 - 11000m	9		6000 - 7000m	9
	11000 - 12000m	10		7000 - 10000m	10
	>12000m	0		>10000m	0
No Data	0	No Data	0		
Layer 3. Property Statistics (for socio-economic factors)	0 - 200m	10			
	200 - 400m	9			
	400 - 1000m	8			
	1000 - 2000m	7			
	2000 - 3000m	6			
	3000 - 4000m	5			
	4000 - 5000m	4			
	5000 - 6000m	3			
	6000 - 7000m	2			
	7000 - 10000m	1			
	>10000m	0			
No Data	0				

**Table 4. Weight Assigned to Each Layer**

Elevator clusters	32
Port terminals	21
Railroad terminals	21
Highways	11
Social and economic factor	15

An additional overlay analysis was done to identify the specific suitable sites and to clean up the final map. First, the suitability map represented which was a raster layer; then it was converted to vector format using the raster-to-polygon tool; and finally, the sites with suitability scores ranging from 7 to 10 (the most suitable sites) were selected to be overlaid with the Brownfields layer. The map in Figure 2 shows the Brownfields that met all five criteria considered in this study for selecting suitable sites for opening new depots in the study region.

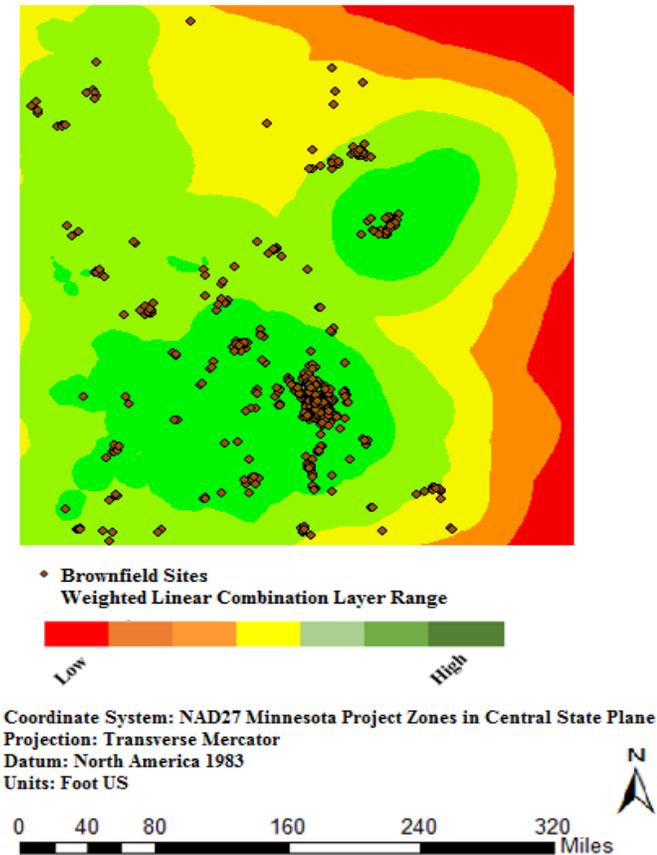


Figure 2. Weighted Linear Combination Analysis Result

## Results and Conclusions

The locational decision-making analysis can be impacted by various criteria, so it is imperative that the stakeholders have tools at their disposal for efficiently determining the potential alternatives. The results of this study showed that there are 90 potentially suitable Brownfield sites for developing the inland empty container depots. Thirty-one of them are most suitable sites and another 59 were classified as less-suitable sites. The total acreage of suitable sites was 2050 acres. Most of these sites in the south are closer to elevators

and the ports, which happens to be the highest weighting factors. The development of new depots on Brownfield sites can solve the container availability problem in the portions of the study area, which will also boost grain exports and support economic activities. Moreover, the opening of new inland depots can also reduce empty-container movements between regional importers, marine terminals, and export customers, which is a non-revenue generating exercise.

The recovery of Brownfields is a way of saving land, especially Greenfield land, which is often habitable and suitable for agriculture and which can help to promote sustainable environments. Brownfields also present a chance for the people in a community to obtain and retain jobs. Research contributes in devising a tool that integrates the weighted linear combination (WLC) into geographic information system (GIS) modeling. By adding/removing or adjusting evaluation criteria, the method can be applied in other fields involving spatial decision making and land value evaluating, such as locating commercial and public facilities, city planning, and optimal public transportation route selection.

## Recommendations for Future Work

This research study used a simplified Euclidean distance instead of traveling distance of road networks. Because road networks are extensive in the state of Minnesota, it was assumed it was not significantly different using this method. If this method were applied to other areas with sparse road networks, the results may be less appropriate. The network analysis in GIS can calculate the shortest routes and shortest travel time from any location to specified facilities. Therefore, in future studies, based on their preferences, users can choose to use either the shortest routes or the shortest travel time to evaluate such factors.

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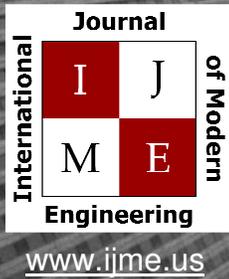
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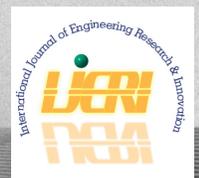
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