System Concepts and the Design of a Household or Classroom Marine Aquarium

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This workshop focuses on the use of a systems thinking approach as part of a systems engineering process to select a system concept for the design of a household or classroom marine (salt water) aquarium. The workshop addresses the needs of the users and maintainers of the aquarium over time, starting with developing the system concept and ending with retirement of the system, to enable the student to select an appropriate system concept for their aquarium design.

Definitions include:

- **System:** A system is a set of independent yet interrelated components working together to accomplish a common purpose – a purpose that could not be accomplished by the independent parts alone.
- **System Context:** The system context defines the boundary of the system, what is inside and what is outside the system, and how the system relates to its external environment.
- **Critical Thinking:** Critical thinking is also called high order thinking or disciplined thinking. We use critical thinking to process our thoughts, senses and feelings about the world around us. Critical thinking is used to question our understanding of the world in order to seek the truth.
- **Systems Thinking:** Systems thinking is critical thinking combined with a strong understanding of system concepts. Systems thinking related concepts we will cover include defining the system context, incorporating multiple perspectives to determine the requirements of the system, and understanding the impact of cause and effect relationships that can change the performance of our system.
- **Stakeholder:** Stakeholders are those individuals involved in the design or use of a system; they have a vested interest in the system. Stakeholders are concerned about the system including what they want to use the system for, how much the system costs to make and use, where the system will be located, what they think is most important about the system, etc…
- **Systems Engineering:** Systems engineering is the process that we use to transform a need or opportunity into an operational system that meets the stakeholder requirements over the life of the system.
- **System Life Cycle:** The system life cycle is made up of phases that a system goes through from the system concept development phase until retirement and/or replacement of the system.
- **Pugh Matrix:** A Pugh Matrix is a table that can be used to compare system concepts to stakeholder requirements. In the Pugh Matrix, each concept is rated for whether it meets, does not meet, or exceeds each requirement.

The system life cycle consists of:

- Develop System Concept
- Design System
- Produce System
- Test System
- Sustain System
- Retire/Replace System

The first three steps of the systems engineering process apply to the first phase of the system life cycle, Develop System Concept, and are:

- Identify a Need or Opportunity
- Identify Stakeholders and Gather Requirements
- Define, Evaluate and Select a System Concept

Coincident with the three systems engineering steps for 'Develop System Context' there are three systems thinking steps:

- Understand the System Context and Define the System Boundary
- Incorporate Multiple Perspectives: both People and System Views
- Recognize and Understand Cause/Effect Relationships

For this complete lesson, the students begin with a mock activity where they are given a limited amount of time to choose the parts of their aquarium. Then the students go through the system engineering and system thinking steps for selecting a system concept. Stakeholders are identified and requirements are gathered using an interview process. Expert advice is included in the requirements gathering process. As the final step in the process, the Pugh matrix is used to select the first household aquarium. Students then compare the selected system concept chosen after applying systems engineering and systems thinking to their original aquarium selections. Students reflect on the differences before/after and lessons learned.

Workshop Objectives:
By the end of the workshop, participants will be able to:

1. Describe the first three systems engineering steps and explain how we use systems thinking at each step to develop our system concept.
2. Discuss the process of gathering stakeholder requirements and balancing multiple perspectives early in the system life cycle.
3. Explain the Pugh Matrix based system concept selection process.
4. Discuss the importance of considering cause/effect relationships in the final selection of the system concept.

These questions will be asked at the end of the workshop:

1. List three things you learned from this overview of using system thinking as part of the systems engineering process to develop a system concept. What one idea do you think you will use the most often?
2. If you could change one thing about this workshop, what would it be?
3. Do you think you will use this lesson plan? Why or why not?

Lesson One: The System Life Cycle

Objectives:
Students will be able to:

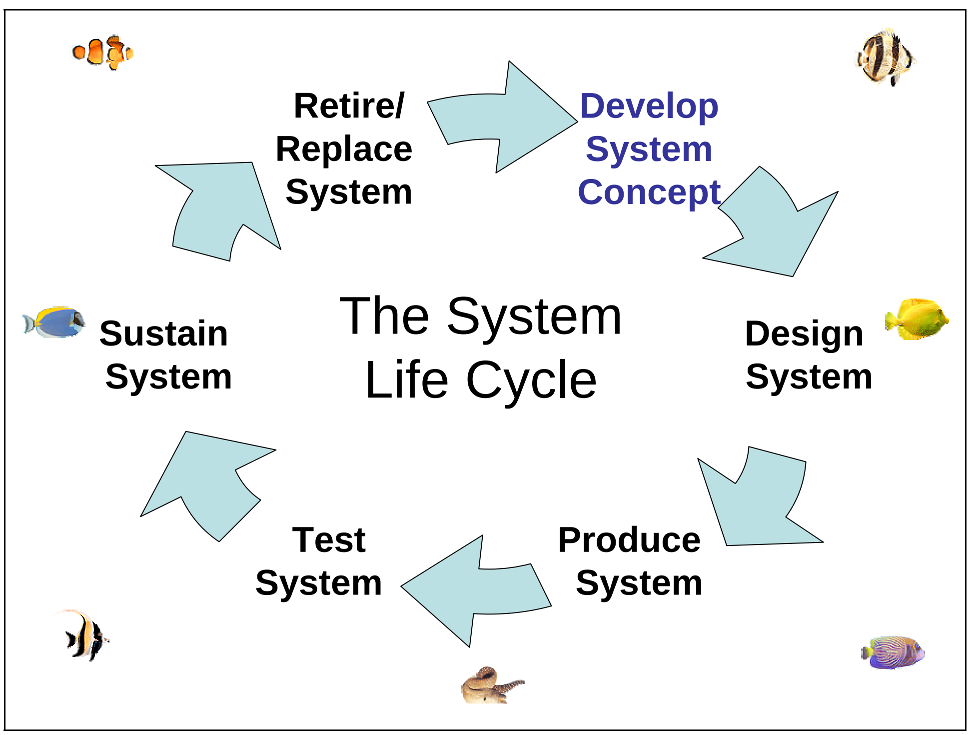
1. Explain what a system is and give examples.
2. Identify the phases of a system life cycle.
3. Define systems engineering and systems thinking.
4. List the systems engineering and systems thinking steps that support developing a system concept.

Materials:
Activity: Marine Aquarium Shopping Spree
Presentation: Lesson One: The System Life Cycle

Background:

What is a System?
The phrase "The whole is greater than the sum of the parts." applies to many systems. A system is a set of independent yet interrelated components working together to accomplish a common purpose – a purpose that could not be accomplished by the independent parts alone. When the system is organized properly, the system as a whole performs better than the sum of its parts. The marine aquarium is one example of a system.

The System Life Cycle
Systems follow a system life cycle such as the one shown below.



Selecting the type of aquarium to design for the household or classroom is part of the ‘Develop System Concept’ phase. Once a viable concept is selected, various designs for that type of aquarium are investigated in the ‘Design System’ phase, and the final design chosen. The actual gathering of materials and setup of the marine aquarium is completed as part of the ‘Produce System’ phase. The aquarium water quality and ability to sustain life is tested in the ‘Test System’ phase. Once the aquarium is populated with the initial set of live inhabitants and has reached a stable sustainable environment, the aquarium has entered the ‘Sustain System’ phase. This can be a very long phase. When the aquarium is disassembled, that is the ‘Retire System’ phase.

What is Systems Engineering?

Systems engineering is a process that starts at the beginning of the system life cycle. The purpose of systems engineering is to make sure that we design a system that will work. The system was designed for a reason – the needs of the stakeholders. Stakeholders are those individuals involved in the design or use of the system. They have a vested interest in what the system can do. Each stakeholder has a different perspective on what the system should be and what is most important about the system. A successful system balances the multiple perspectives of the stakeholders and meets the overall needs of the stakeholders.

A working definition of systems engineering for the purpose of this lesson is: “Systems engineering is the process that we use to transform a need or opportunity into an operational system that meets the stakeholder requirements over the life of the system.”

The Systems Engineering Process for Develop System Concept

The first phase of the system life cycle is ‘Develop System Concept’. Within this phase, there are three primary steps that are completed as part of the systems engineering process:

- Identify a Need or Opportunity
- Identify Stakeholders and Gather Requirements
- Define, Evaluate and Select a System Concept

The systems engineering process starts with understanding the need or opportunity that the system is being designed for. In this case, there is a pre-existing need or opportunity for a classroom or household marine aquarium. The next step is identifying the stakeholders (those individuals involved in the design or use of the system) and gathering their requirements. Experts should be part of the requirements gathering process. Requirements that span the life cycle of the system should also be included in the requirements gathering process. The final step is defining and evaluating viable system concepts and selecting the system concept that we are going to design to. This step is reviewed in the final lesson.

These three steps apply to the design of a marine aquarium and provide an introduction to systems engineering. However, there are many more steps in the systems engineering process at each phase of the system life cycle.

Systems Thinking and the Systems Engineering Process
Systems thinking is critical thinking combined with a strong understanding of system concepts.

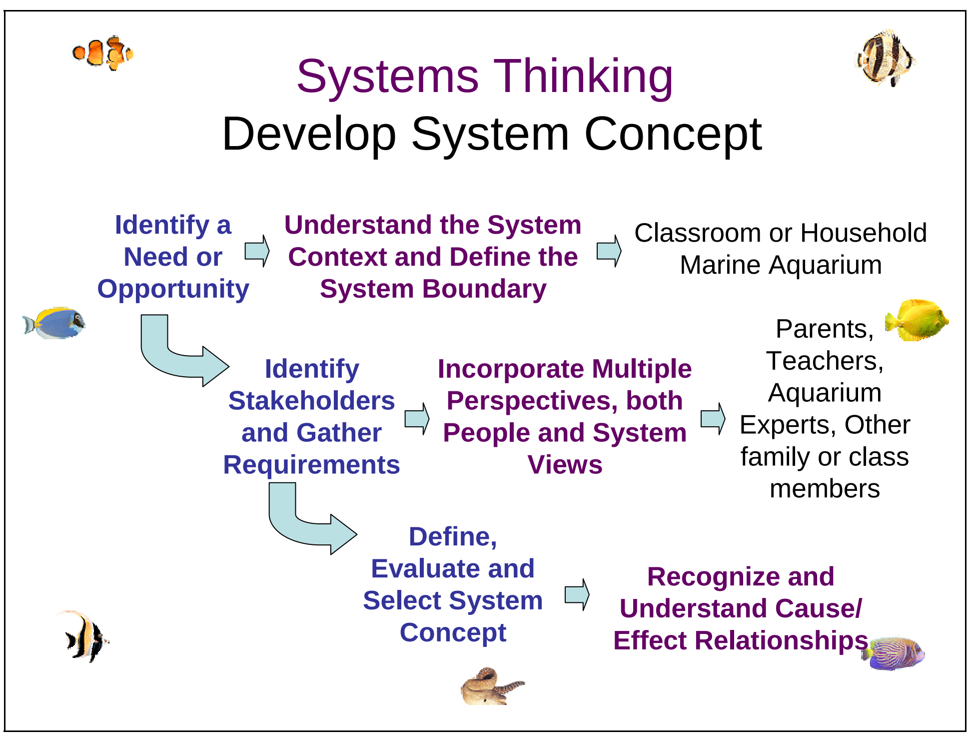
What is critical thinking? Critical thinking is sometimes called higher order thinking or disciplined thinking. Critical thinking is more than just memorization or recalling facts. We use critical thinking when we question statements, integrate ideas, and evaluate alternatives. The idea of critical thinking is that of a watchful mind, always on alert – putting the inputs to the mind through an evaluation process. We use critical thinking to process our thoughts, senses and feelings about the world around us. Critical thinking is used to question our understanding of the world in order to seek the truth.

When you combine critical thinking with an understanding of systems and system concepts, you have systems thinking. Systems thinking is the backbone of many systems related disciplines, including systems engineering.

Systems thinking is part of the systems engineering process at every step of the way. Coincident with the three systems engineering steps for 'Develop System Context' there are three systems thinking steps:

- Understand the System Context and Define the System Boundary
- Incorporate Multiple Perspectives: both People and System Views
- Recognize and Understand Cause/Effect Relationships

The systems engineering and systems thinking steps are shown together shown below:



When we define a need or an opportunity for a system, we need to understand the type of environment that the system will have to operate in. We have to bound the system. We need to understand what the system will do, and what it will not do; we need to understand what parts of the environment belong in the system and what parts of the environment will be outside of our system. The system boundary and the type of environment the system will operate in form what we call the system context. We use systems thinking to understand the system context and this helps us to better define the need or opportunity for our system.

Another aspect of systems thinking that comes into play when gathering our stakeholder requirements is the ability to understand multiple perspectives. Our stakeholders will each have varying backgrounds, different personalities and goals, and they will have different requirements for our system. Sometimes the requirements of the stakeholders will be directly opposing. Understanding multiple perspectives can help us make it through this step of the systems engineering process. We will want to be able to find ways to satisfy all the stakeholders so that we will be able to build our marine aquarium.

We will also need to understand multiple perspectives for identifying all of the possible system concepts that we can use for designing our system. In order to define, evaluate and select a proper system concept from the set of concepts identified, we will need to understand the cause and effect relationships that apply to our system or to each system concept. For example, the location of our aquarium (direct sun, indirect sun, shade) and the temperature of the surrounding air can affect the temperature of the water in our aquarium. As the external temperature rises, the internal temperature rises, and vice versa. We will need a way to keep the temperature of our water at the right level to keep the aquarium inhabitants alive.

Procedure:

1. Students participate in Marine Aquarium Shopping Spree. Use the 'Marine Aquarium Shopping Spree' questionnaire as needed. For example, the instructor can provide a way for students to select parts of their aquarium and build their own aquarium. One way is to provide magnetic boards with various magnets of the aquarium choices including size, lighting, equipment, and various types of inhabitants. Another way could be the use of construction paper cutouts that are provided. This activity should be limited to 10 minutes. The important aspect is to limit the amount of time so that the students have to make quick decisions without much time to think about the consequences of those decisions.
2. Instructor provides an introduction for the lesson which should include an overview of all three steps of the systems engineering process and each concurrent step of systems thinking concepts that support developing the system concept; this information is found in the "Background" section above and the provided presentation charts.
3. After the introduction, the instructor breaks the class into groups of 2 – 3 students to develop responses to the assessment questions listed below. These can also be assigned as homework if the lessons are given over multiple days.
4. Instructor leads a class discussion to review student responses to the assessment questions. Note: There is no one right answer to the assessment questions. The important aspect is that the student can justify their answer.

Assessment Questions:

1. What are other examples of systems found in nature?
2. What are other examples of man-made systems?
3. Is the World Wide Web (the internet) a system? Why or why not?
4. Give an example of a system that does not follow the rule: "the whole is greater than the sum of its parts."
5. Describe what systems engineering means to you, in your own words.
6. Give an example of how you might use systems thinking to solve a problem.
7. Your class is designing a classroom aquarium, what plans do you need to make to sustain the aquarium after the end of the school year?

Implementation Tips:

Completing the shopping spree first is important. This activity is intended to mimic what can happen on a project in real life. A business or family may make quick decisions about complex projects – due to perceived or real time constraints – only to result in a final product that is not acceptable and even more time and money is spent 'fixing' the product. The shopping spree activity allows the students to go through a similar experience only to find out – once they refer back to these purchase selections at the end of the lessons – that their informed choices, made after following a proven process, would have been very different. The goal is for the students to realize that the amount of effort to get to a better informed position was not too great or costly, and the small amount of effort put in at the beginning makes a huge difference in the end. This is the value of using systems thinking as part of a systems engineering process.

Lesson Two: Identifying Stakeholders and Gathering Requirements

Objectives:
Students will be able to

1. Explain what a stakeholder is and list examples of stakeholders.
2. Describe a general process for collecting stakeholder requirements.
3. Discuss the importance of balancing multiple perspectives.
4. Explain the role of expert advice in selecting the right system concept.

Materials:
Presentation: Lesson Two: Identifying Stakeholders and Gathering Requirements
Take Home or In class Activity: Requirements Survey

Background:

What is a Stakeholder?
Stakeholders are those individuals involved in the design or use of a system. Here are some questions you can ask to determine who the stakeholders are:

- Who is paying for the aquarium? (Payee) Someone needs to pay for all the parts of the aquarium.
- Who is the aquarium for? (Customer/Owner) The person, for whom the system is being designed, is the customer. The customer is usually the person that owns the system once it is complete.
- Who will maintain the aquarium? (Maintainer) A marine aquarium has daily and weekly maintenance activities that must be completed to keep a well maintained aquarium. Without proper maintenance the aquarium inhabitants will die, and even with the best environment there can be unexplained mortality.
- Who provides parts for the aquarium? (Parts Provider) This includes the manufacturers who make products for the aquarium.
- Who provides expert information about the aquarium? (Expert/Trainer) The pet store employees, authors of books on aquariums, and relatives or friends who have aquariums are examples of experts who help you make the aquarium successful.
- Who is designing the aquarium? (Designer) This is usually a team of people that includes the payee, the maintainer, the user and the aquarium expert.
- Who establishes rules for the aquarium? (Legal/Standards Body) There may be certain guidelines or rules to follow in the design or use of the aquarium. For example, parents may have special rules about a child taking care of the aquarium before leaving for school each morning. Or the house the aquarium is being placed in may have related size or weight restrictions.
- Who will use or view the aquarium? (User) The users of the system, in this case those who will be viewing the aquarium, are often overlooked as stakeholders of the system. Yet it is the users of the system who will decide whether the system is a success or failure. This group of stakeholders should not be overlooked!

For the classroom aquarium, stakeholders include not only the classroom students and teacher, but also the school administration and principal, the students' parents, possibly the school board or other governing body, whomever is paying for the aquarium, the maintainers of the aquarium is that is someone different, the local aquarium expert, etc…

For the household aquarium, the stakeholders are typically all members of the family, possibly the extended family (grandparents, aunts, uncles, cousins, etc..), other pets may be considered stakeholders, friends who come to visit the household, the landlord if applicable, possibly other homeowner governing bodies, the local aquarium expert, etc….

Stakeholder Requirements

Once the stakeholders are identified, the next step is to collect the stakeholder requirements. One challenge in collecting stakeholder requirements is that many times stakeholders do not realize all of their requirements until they see the system in action. However, once the aquarium is set up and running, it is too late to find out that your stakeholder has a requirement that you can no longer meet! When it comes to setting up a marine aquarium, a redesign can prove timely, costly, and sometimes impossible. Therefore you need to make sure you gather a complete set of requirements. Another challenge is that stakeholders do not always appear to agree on the requirements for the system. One important aspect of systems thinking is the ability to incorporate multiple perspectives. When stakeholders do not agree we need to dig deeper to understand their true requirements which will help us balance the multiple perspectives.

There are methods you can use to help your stakeholders think about all of their requirements. One method is to interview the stakeholders. Before interviewing stakeholders a set of related questions should be prepared. These questions should take into account all the many types of stakeholders that are interested in your system. These questions should span many different areas that must be considered before designing your aquarium.

During the interview, in order to better understand your stakeholder's perspective, talk to your stakeholders about different types of marine aquariums, show them pictures of what various aquariums might look like, talk about how the aquarium will be set up and maintained, and share other ideas you have for your marine aquarium. The questions and information you provide will help your stakeholders visualize the marine aquarium when it's in operation, and that visualization will help the stakeholder to communicate their requirements more accurately. However, the main way to understand your stakeholder's perspective is to listen. Sometimes, especially if you have opposing requirements, you need to dig deeper. Asking 'why' up to five times can help you get a better understanding of your stakeholder's requirements so that you can balance the multiple perspectives from the many stakeholders and come up with a good solution.

It is important that the interviewer write or record the stakeholder's comments in order to capture and remember all of the stakeholder requirements.

Stakeholder requirements are typically grouped into categories. Here are some examples of requirements in each of the categories shown on the Requirements Survey:

- General: "The aquarium shall have the soft soothing sound of rushing water at all times."
- Cost: "The aquarium shall cost no more than twice the amount of our current freshwater aquarium."
- Time: "The aquarium shall take no more than one day to set up."
- Environmental Impact: "The aquarium shall only have inhabitants that were bred in captivity."
- Aesthetics (looks): "The aquarium shall look really cool."
- Performance: "The aquarium shall make me feel happy."
- Location: "The aquarium shall be at eye level when I sit down."
- Maintenance: "The aquarium shall be relatively easy to maintain."

In some cases the requirement is easy to measure or visualize. In other cases, you may need to find out more information about the requirement. For example, what is meant by 'really cool' or 'easy to maintain'? When interviewing stakeholders, try to understand what the stakeholder really means.

Ask The Expert

Before you conduct your stakeholder interviews, you should be knowledgeable about the system that you are designing. Requirements should also be collected from experts and through research. A successful marine aquarium requires an in-depth understanding of the requirements of the marine environment and the creatures that live there. Here are some important facts on marine aquariums:

- The compatibility of the marine life in the aquarium is the single most important consideration – since there is only one environment. This includes such factors as lighting, water quality, and aggressiveness of marine life and their diet.
- Water quality is the most important factor for keeping the aquarium inhabitants alive. This includes monitoring and controlling the level of ammonia, nitrite and nitrate and the pH level, as well as the temperature and salinity of the water. Before you can add many fish, the aquarium must first 'cycle' through high levels of ammonia, then nitrite, both of which are harmful to the fish, and then finally nitrate which is not harmful to the fish.
- Salt water friendly equals salt water safe! Do not include any item in your marine aquarium that has coatings or preservatives that may result in harmful leaching of substances into the salt water. Do not include items that contain metal, no matter how little. Be sure to sterilize any item before placing it in your tank.
- The amount of fish in the water has a direct effect on the water quality. More fish means more excess food and more waste, both of which need to be cleaned from the environment. Guidelines for the amount of fish are:
  - Freshwater: 1 inch of fish per gallon of freshwater
  - Fish-only Marine: 1 inch of fish per three gallons of salt water
  - Mixed (corals with some fish): 1 inch of fish per five gallons of salt water
- The amount of natural lighting, weight bearing capacity and external temperature fluctuation are important considerations when choosing a location for the aquarium.
  - To calculate weight: 8.5 pounds per gallon of sea water, plus additional weight of tank, results in the rule of thumb of 10 pounds per gallon of water.

You can also check out and read books from your school or local library on marine aquariums or marine fish. The World Wide Web (internet) is a good place to find free information on marine aquariums. Be sure to avoid online ads and make sure you use ‘safe’ websites as you would whenever you use the internet.

Procedure:

1. Instructor provides an introduction for the lesson which should include an overview of identifying stakeholders, a discussion of the importance of incorporating multiple perspectives, and the process of gathering a broad set of requirements; this information is found in the “Background” section above and the provided presentation charts.
2. Instructor reviews the ‘Requirements Survey’.
3. After the introduction, the instructor breaks the class into groups of 2 – 3 students to develop responses to the assessment questions listed below. These can also be assigned as homework if the lessons are given over multiple days.
4. Instructor leads a class discussion to review student responses to the assessment questions. Note: There is no one right answer to the assessment questions. The important aspect is that the student can justify their answer.
5. Students gather requirements for their aquarium using the Requirements Survey as a starting point. This can be accomplished by either forming groups in class and having each member play a stakeholder role, or as a homework assignment where family members or other stakeholders are interviewed.

Assessment Questions:

1. Make a list of stakeholders for the aquarium, by name. Who is the most important stakeholder for your salt water aquarium? Why?
2. Are the fish and other living sea creatures in your marine tank stakeholders? Explain.
3. How are gathering a set of complete requirements and balancing multiple perspectives related?
4. Add 3 new questions to your requirements survey that will help you collect stakeholder requirements.
5. What else can you do to make sure you are not missing requirements?
6. Name 3 sources of expert information you can use to research information on your aquarium.
7. What are your top 3 requirements for your marine aquarium? Use the questions on the requirements survey to give you some ideas.

Implementation Tips:

For the household or classroom aquarium, the class can form into groups and each group member can take on a particular role in the classroom – teacher, student, principal, janitor, etc… or in the household – mom, dad, brother, sister, grandparent, etc… Then the group members can take turns interviewing each other to gather the stakeholder requirements. It’s important to focus on only the top 2 to 3 requirements for each stakeholder. The more stakeholders there are, the less ‘top’ requirements that should be collected from each one so that the students end up with between 5 to 12 ‘top’ requirements, including their own.

Lesson Three: Choosing Your First Aquarium

Objectives:

The student will be able to

1. Explain what a Pugh matrix is and how it can be used.
2. Complete a system concept selection process using the Pugh matrix.
3. Discuss the cause/effect relationships that impacted the system concept selection process.

Materials:

Presentation: Choosing Your First Aquarium
Worksheet: Completing the Pugh Matrix

Background:

The Pugh Matrix

Once the aquarium research is complete and the requirements are collected from the stakeholders, you will select what type of aquarium to start with. To assist with the selection process you can use the Pugh matrix. The matrix is a table used to organize the information for making an informed decision. Stuart Pugh introduced this matrix in 1991 as a way to help compare alternatives when there is not a lot of detailed information. The Pugh matrix separates the alternatives from the criteria. We will be using requirements as the criteria to select between the alternatives for our aquarium.

The first column of the Pugh matrix is used to list the criteria or requirements, one requirement for each row of the table. The rest of the columns are used to gather information for each alternative or concept, with each column representing a different concept.

Populating the Pugh Matrix

To populate the Pugh matrix start by listing the alternatives – in our case our system concepts – along the top row of the table, skipping the first column. Next write the criteria – in our case our requirements – down the first column, one requirement per row. Next, decide whether each system concept alternative is more than meets the requirement (+), meets the requirement (S) or does not meet the requirement (-). Once you are done, count the number of each, for each system concept, and write the sums down in the last three rows of the table. Please refer to the example on the following page.

Selecting Your Concept

Can you use the sums from the table to find out the 'right' answer? While a Pugh matrix is useful in structuring the concept selection process, Pugh cautions against using the sums of each rating to make decisions. When using a Pugh matrix, the preferred concept should be selected 'informed by' but not 'determined by' the matrix.

For example, just because one concept has the most '+'s does not mean that is the concept that should be selected. The user of the Pugh matrix is the best judge of the right concept to select. The table simply provides a method for viewing and summarizing the information available at that time.

Pugh Matrix

	Concept 1	Concept 2	Concept 3	Concept 4
Requirement 1	+	-	+	-
Requirement 2	+	S	+	S
Requirement 3	-	+	-	-
Requirement 4	-	+	+	-
Requirement 5	+	-	+	-
Total +	3	2	4	0
Total S	0	1	0	1
Total -	2	2	1	4

Use '+' for better than requirement
Use 'S' for meets the requirement
Use '-' for does not meet the requirement

Example: Selecting a Pet

As an example, use the Pugh matrix to help decide what type of pet best fits the requirements:

Example: Selecting a Pet

	Dog	Cat	Snake	Fish
Can take for a walk	+	-	-	-
Provides companionship	+	S	-	-
Can leave home alone for long periods of time	-	S	+	+
Can take for a car ride	+	S	-	-
Easy to take care of	-	S	S	+
Total +	3	0	1	2
Total S	0	4	1	0
Total -	2	1	3	3

Use '+' for better than requirement
Use 'S' for meets the requirement
Use '-' for does not meet the requirement

As shown, based on our requirements, we find that the dog exceeds on three requirements, but does not meet two requirements. The cat does not exceed requirements in any area, but meets 4 out of the 5 requirements. Yet the snake and the fish can be left home alone for long periods, much longer than the amount of time we might be able to leave a dog home without disastrous consequences (to the dog or to our house!). However, the snake does not meet three requirements. The fish are enjoyable to watch and comparatively easy to take care of but do not meet 3 out of 5 requirements. Which one would you choose?

Here are some example choices using the previous Pugh Matrix as a guide to select a pet:

- Michael chose the dog, as a dog offers the best match to his requirements and he will make sure not to leave the dog home alone for long periods of time.
- Joshua chose the fish as he has to be able to leave his pet home alone for long periods of time and most of all he wants something he will enjoy watching.
- Justin chose the cat because he only wants some companionship, not too much, and he wants the flexibility to take his pet with him or leave the pet at home.

Notice that to Michael, Joshua and Justin, certain requirements are more important than other requirements and this level of importance influences their final choice.

Considering Cause/Effect Relationships

Cause/effect relationships can impact only the system, or they can affect the environment in which the system resides.

For our Pet Selection exercise, many cause/effect relationships exist. For example, in every case a pet requires a time commitment on the part of its owner or caretaker. Some pets need to be potty trained if they are to be part of the household. Others need behavioral training in order to act appropriately around people. Some pets require companionship while others want to be left alone. Most pets require some type of daily feeding and a clean, safe environment in which to live.

Other cause/effect relationships that should be considered are household or classroom members may be allergic to certain pets or products put on the pets or even the food used to nourish the pets. And pets are wild animals and can behave in an unsafe manner under certain circumstances.

Ultimately, an understanding of cause/effect relationships will aid in the final selection of a system concept. Michael, Joshua and Justin may change their choices based on a consideration of cause/effect relationships

Using the Pugh Matrix to Select the First Aquarium Type

Based on the collected requirements, use the Pugh matrix to select an aquarium.

The aquarium choices for this activity will be:

- **Marine Fish-Only:** Contains only fish. Examples include: a) a community of compatible marine fish with similar environmental needs that all get along, or b) a single specimen that is better kept alone because it is large and aggressive or predatory. This type of aquarium may optionally contain benign crustaceans (like shrimp or crabs) and/or benign Mollusks (like clams or oysters). This aquarium may not have the look that you are trying to achieve.

- **Marine Mini-Reef/Corals:** Contains hard and soft corals, sponges, anemones and other types of sessile (non-moving) invertebrates (no backbone). This type of aquarium does not typically contain fish of any kind. The mini-reef requires intense lighting to keep the sea life alive. This aquarium may not have the look that you are trying to achieve.

- **Marine Mixed (Fish and Mini-Reef):** A mixed aquarium is a mini-reef/corals aquarium that has fish. In its simplest version the fish do not feed on the coral. This aquarium has the most likeness to a marine ecosystem and setups can range from simple to very complex. The mixed aquarium is the most difficult to maintain because the water quality and temperatures as well as lighting must be kept at very specific levels. There is more chance of failure in this type of complex marine ecosystem, including unexplained mortality and missing sea creatures.

- **Freshwater:** This is the easiest aquarium to start with and guarantees the best chance for success. However, many aquarium enthusiasts start with a marine aquarium after they have done their research. Since the freshwater aquarium is the more common type of household aquarium, there is better availability of both inhabitants and equipment. Fish are generally less expensive and the aquarium itself is generally easier to maintain. Also, you can have more fish per gallon of water in a freshwater aquarium. On the other hand, the aquarium may not have the look you are trying to achieve and you may lose interest.

Pugh Matrix Afterward

Whenever defining concepts for the Pugh matrix, they should be well defined before applying the Pugh matrix process. It is important to use a broad set of concepts to choose from. It is not unusual to repeat the process to add new choices based on combinations of the original choices or new ideas, to include new requirements not previously considered or thought of, or to change ratings based on new information.

Procedure:

1. Instructor provides an introduction for the lesson which should include an overview of how to apply the Pugh matrix to select the type of aquarium and a discussion of cause/effect relationships; this information is found in the "Background" section above and the provided presentation charts.
2. Complete the "Choosing your First Aquarium" handout.
3. After the introduction, the instructor breaks the class into groups of 2 – 3 students to develop responses to the assessment questions listed below. These can also be assigned as homework if the lessons are given over multiple days.
4. Instructor leads a class discussion to review student responses to the assessment questions. Note: There is no one right answer to the assessment questions. The important aspect is that the student can justify their answer.

5. Instructor leads discussion with students on the differences between the original selections of the aquarium, and the final system concept selected. Students discuss the lessons they learned from the experience.

Assessment Questions:

1. Provide an example where using the Pugh matrix could help you make a decision. List three or more different alternatives or concepts you might select from.
2. When using the Pugh matrix, you could always choose the concept with the least number of '-'s (does not meet the requirement). Is it a good idea to use a rule such as this for making your final selection using the Pugh matrix? Why or why not?
3. What are your top three requirements for a pet?
4. What pets would you include in the selection process?
5. Using the 'Selecting a Pet' Pugh matrix as a guide, which pet would you select and why?
6. What if you cannot decide between two types of aquariums? What will you do? What will the impact be?
7. What cause/effect relationships did you consider when selecting your aquarium concept?
8. Now that you have selected your first marine aquarium, go back and review your shopping spree purchases. What items can you keep? What items do you need to return? Why?
9. List three things you learned from your introduction to systems engineering and systems thinking. What one idea do you think you will use the most often?
10. Why is systems engineering important?
11. Why is systems thinking important?
12. What questions do you still have?

Implementation Tips

Additional research on the marine aquarium prior to completing the concept selection process will be of benefit to the students, if time allows. The marine aquarium shopping spree could be retaken by the students so that they can directly compare how their purchases would change now that the have gone through the systems engineering process for designing a marine aquarium.

Additional or Enhanced Activities

Some ideas for additional activities include:

1. Students can do additional research, in groups or individually, on these challenge topics:
    - Breeding in the Marine Tank
    - Diagnosing Ailments
    - Photographing Fish
    - How Biological Filtration Works
    - Venomous Fish and other Sea Creatures
    - Conservation of the World's Coral Reefs
    - The Marine Aquarium and Stress Relief
    - The Impact of the Marine Aquarium on the Ecosystem

2. The next step in the systems engineering process is to define the various functions that will be performed on the marine aquarium. The students can define the steps for supporting these activities which include:
    - Cycling the Tank
    - Testing Water Parameters
    - Selecting Compatible Specimens
    - Treating Ailments
    - Changing Water
    - Feeding the Fish
    - Cleaning the Tank
    - Emptying the Protein Skimmer
    - Turning the Lighting On/Off

3. The class could plan for and build an aquarium in the classroom, making sure to plan what will happen to the aquarium and its inhabitants at the end of the school year. Many lessons can be tailored around the 'closed' marine aquarium ecosystem and students can be directly involved in the care of the marine aquarium. At the end of the year, each student could summarize what they learned, and provide lessons learned, hints and guidelines for next year's class.

Marine Aquarium Shopping Spree

You have just won a free shopping spree from your local pet store. You have 10 minutes to purchase items for a new marine aquarium. What will you buy?

A tank of this size (choose one):
- ☐ 1 to 9 gallons
- ☐ 10 to 50 gallons
- ☐ 51 to 100 gallons
- ☐ Greater than 100 gallons

To hold my aquarium (choose one):
- ☐ A stand
- ☐ A cabinet
- ☐ A stand with aquarium built in
- ☐ A wall mount kit

This type of lighting (choose one):
- ☐ No lighting
- ☐ Spot light (only lights part of tank)
- ☐ Standard fluorescent
- ☐ High-intensity lighting

These filters (choose all that apply):
- ☐ Under gravel Filter
- ☐ Wet/dry filter system
- ☐ Reverse Osmosis Water Filter
- ☐ Protein skimmer
- ☐ Other____________________

Other equipment (choose all that apply):
- ☐ Submersible Heater
- ☐ Thermometer
- ☐ Power Heads
- ☐ Hydrometer
- ☐ UV Sterilizer
- ☐ Other____________________

These water quality test kits (choose all that apply):
- ☐ Ammonia
- ☐ Nitrite
- ☐ Nitrate
- ☐ pH

Decorations (choose all that apply):
- ☐ Aquascape (picture background)
- ☐ Treasure Chest
- ☐ Scuba Diver
- ☐ Sunken Boat
- ☐ Other __________________

This type of sand (choose one):
- ☐ Living sand
- ☐ Part living, part non-living sand
- ☐ All non-living sand
- ☐ Crushed coral

These coral (choose all that apply):
- ☐ Bubble Coral
- ☐ Soft Coral
- ☐ Brain Coral
- ☐ Other __________________

These fish (choose all that apply):
- ☐ Angelfish
- ☐ Shark
- ☐ Butterfly fish
- ☐ Clown fish
- ☐ Pufferfish/Blowfish
- ☐ Goldfish
- ☐ Moorish Idol
- ☐ Parrotfish
- ☐ Sunfish
- ☐ Trigger Clown
- ☐ Yellow Tang
- ☐ Moray Eel
- ☐ Other __________________

Other sea creatures (choose all that apply):
- ☐ Sea Anemone
- ☐ Shrimp
- ☐ Crab
- ☐ Starfish
- ☐ Other __________________

Marine Aquarium: Requirements Survey

Use these questions to collect the top 3 requirements from at least 2 household or classroom members. Add your own questions to this list and be sure to gather requirements for all phases of the aquarium life cycle.

General:
What do you like about having an aquarium?

What is one thing you want to make sure this aquarium has or does?

Cost:
How much should the aquarium cost initially?

How much should it cost to operate the aquarium weekly or monthly?

How much should new fish or other sea creatures cost?

Time:
How long should the initial set up of the aquarium take?

How much time should it take to maintain the aquarium?

How often and for how long will the aquarium be viewed?

How long should we have an aquarium?

Environmental Impact:
How does acquiring aquarium inhabitants impact the marine ecosystem?

How might the aquarium be used to support the marine ecosystem?

Performance:
How long should the inhabitants typically survive?

What type of fish and other sea creatures can live together in one environment?

Aesthetics (looks):
How do you want the aquarium to look?

How many fish would you like to see in the aquarium?

What type of sea creatures would you like to watch in the aquarium?

What type of decorations do you want in the aquarium?

Size/Location:
How big should the aquarium be and where should the aquarium be located? Why?

What activities do you want to be able to do in the aquarium location?

How much natural light should the aquarium have?

Can the flooring and things around the aquarium get wet? With salt water?

How often will you need to move the aquarium?

Maintenance:
How will the aquarium be kept 'well maintained' daily? Weekly? Monthly?

Who will be responsible for water quality?

How often should the water be tested?

Choosing your First Aquarium

1. List your most important 5 to 12 stakeholder requirements down the left hand side of the Pugh matrix.
2. Analyze each concept against each requirement and decide which rating (see legend at bottom) is most appropriate.
3. Fill in the table with these ratings.
4. Sum the number for each concept in the final three rows.
5. On the back of the page, describe which concept you selected and why.

Stakeholder Requirements:	Marine Fish Only	Marine Corals	Marine Mixed	Fresh water	Other
Total +					
Total S					
Total -					

Use ‘+’ for better than requirement
Use ‘S’ for meets the requirement
Use ‘-’ for does not meet the requirement

Reference: National Science Standards (Grades 6 – 12)

Lesson 1:
CONTENT STANDARD A (Science as Inquiry):
As a result of the activities, students should develop:

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

CONTENT STANDARD E (Science and Technology):
As a result of the activities, all students should develop:

- Abilities of technological design
- Understandings about science and technology

Lesson 2:
CONTENT STANDARD A (Science as Inquiry):
As a result of the activities, students should develop:

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

CONTENT STANDARD C (Life Science):
As a result of the activities, should develop understanding of:

- Regulation and behavior
- Populations and ecosystems

CONTENT STANDARD E (Science and Technology):
As a result of the activities, all students should develop:

- Abilities of technological design
- Understandings about science and technology

Lesson 3:
CONTENT STANDARD A (Science as Inquiry):
As a result of the activities, students should develop:

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

CONTENT STANDARD C (Life Science):
As a result of the activities, should develop understanding of:

- Regulation and behavior
- Populations and ecosystems

CONTENT STANDARD E (Science and Technology):
As a result of the activities, all students should develop:

- Abilities of technological design
- Understandings about science and technology