A Strategic Framework for Effective Sketch Modeling

by

Emma Pearl Willmer-Shiles

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Mechanical Engineering

at the
Massachusetts Institute of Technology

June 2018

© 2018 Massachusetts Institute of Technology. All rights reserved.
A Strategic Framework for Effective Sketch Modeling

by

Emma Pearl Willmer-Shiles

Submitted to the Department of Mechanical Engineering
on May 11, 2018 in Partial Fulfillment of the
Requirements for the Degree of
Bachelor of Science in Mechanical Engineering

ABSTRACT

MIT’s undergraduate mechanical engineering capstone class titled 2.009: The product Engineering Process introduces students to the process and tools used by designers to successfully design a product. One of the main skills introduced to students is prototyping as a means of learning about and communicating a product vision. Early stage prototypes, called “sketch models” in 2.009, are made and used in the concept selection phase to explore and validate the design teams concepts. At this point students are new to the design process and unsure of how to develop physical models that are not merely physical representation of their concepts but also tools for exploring, answering design questions and validating a concept. To help students arrive at more effective sketch models this framework has been developed to outline a set of actionable steps that allow students to apply key concepts in the design process to their sketch models.

The first portion of the framework focuses on guiding students to arriving at a useful and strategic learning objective for the sketch model. Students are first guided to consider four main areas of concern for concept validation: market, feasibility, scope and customer need in order to target major areas of uncertainty in their concept. To focus on questions that directly relate to a physical model, the next level of consideration focuses on appearance, user experience and functionality of the concept. Lastly, students use the criteria of uncertainty, criticalness to concept validation, and learning potential to prioritize questions for the current design phase. The second portion of the framework suggest the use of examples of other sketch models with similar learning objectives to demonstrate how models have answered similar questions to those that the design team has proposed. Grouped by their physical area of exploration and categorization as “looks like” or “works like” models, a set of examples will conceptually demonstrate how to make their sketch models effective in answering similar design questions.

Thesis Supervisor: David Wallace
Title: Professor of Mechanical Engineering
Acknowledgments

Thank you to Josh Ramos in assisting with the formulation of the project and to both Josh and Professor Wallace for help in conceptual development of the sketch modeling framework and advice throughout the project. Thank you to Jane Kokernak for writing and communications instruction as well as input on 2.009 sketch modeling from a communications perspective. Finally, thank you to the 2.009 students who shared their observations and experiences in the class to help create a useful tool for future students.
# Table of Contents

Abstract 3  
Acknowledgements 4  
Table of Contents 5  
List of Figures 6  
1. Introduction to the 2.009 Process 7  
2. Introduction to Sketch Modeling 9  
3. Framework 10  
  3.1 Part 1 12  
    3.1.1 Characterizing Uncertainty 12  
    3.1.2 Physical Areas of Emphasis 15  
    3.1.3 Prioritizing 17  
  3.2 Part 2 21  
    3.2.1 Physical Categories 21  
    3.2.2 Model Types 22  
    3.2.3 Example 1: Mason Frame 23  
    3.2.4 Example 2: Four Leaf 24  
    3.2.5 Example 3: Piece by Piece 25  
4. Guide For Student Use 27  
5. Conclusion 32  
6. References 35
List of Figures

Figure 1: Diagram of sketch modeling framework 11
Figure 2: Example prioritization Pugh Chart: *Four Leaf* 20
Figure 3: Example 1: *Mason Frame* images 24
Figure 4: Example 2: *Four Leaf* images 25
Figure 5: Example 3: *Piece by Piece* images 26
Figure 6: Diagram of part 1 of sketch modeling framework 28
Figure 7: Example prioritization Pugh Chart: *Fire Sensing* 31
Figure 8: Diagram of part 2 of sketch modeling framework 31
1. Introduction to the 2.009 Design Process

In their final year the undergraduate mechanical engineering majors of MIT participate in the departments capstone class titled 2.009: The Product Engineering Process. This class has various learning goals centered around creating an environment similar to that of a product design firm. One of the many learning objectives, and the one focused on in this paper, is to “improve expertise in constructing models for reasoning about design alternatives”[1]. This objective has a desired physical model making skill set as well as a conceptual understanding of the roll of prototypes in product design as useful tools for learning, testing, and communicating ideas.

Prototyping, a design method that utilizes physical models of a product concept, is iterative and ongoing throughout the design process. Designers create prototypes for the purpose of: learning, communication, integration and milestones[2]. For 2.009 students, sketch modeling is the first stage of prototyping when they are exploring and developing various product concepts. As sketch modeling occurs early in the design process, 2.009 focuses on the learning potential of prototyping to assist in the concept validation and selection process.

Before the sketch modeling milestone, students go through a brainstorming exercise and the first “3-Ideas” milestone. Brainstorming is a concept generation exercise in which students are encouraged to observe users and come up with hundreds of ideas based on the class theme. Past themes have included “super!”, “rough, tough and messy”, “magic” and “adventure”[3]. By initiating the brainstorming process with user observation the class places an emphasis on human-centered design and concepts based on a user need. With the observations students come up with as many product concepts as possible accompanied with rough sketches and short descriptions. The sketches are for communication purposes and not representations of the
physical form of the product concept. The goal is to avoid any judgments and produce a high quantity of varying concepts.

The first major milestone in the class is the “3-Ideas” presentation in which teams are given two minutes to present three concepts from a poster. While providing students with practice for their communication skills via the short 40 second pitches and the design of the posters, the milestone forces teams to go through a concept selection process to narrow down their collective list of hundreds of concepts to just three for the presentation. At this point concept selection and the presentation is based on knowledge of the team and initial research on the market or other relevant technical details.

The “Sketch Model” review is the first chance students have to create physical models for their concepts. Similar to the 3-ideas presentation teams choose three concepts to model and present. These can be the same as from the first milestone or new ones can be introduced. “Sketch modeling” is a term used in 2.009 to describe quick and easy to make models that are used as learning tools to help further investigate a design concept. This milestone and the sketch models are an early part of the design process meant explore and validate the most promising concepts identified by the design team.

Students make the sketch models and present them in a semi-formal presentation to the class, instructors and mentors. For this reason the models should be thought of as learning tools for the design teams and as communication tools to explain and demonstrate product ideas to reviewers. In conjunction with the verbal and slide presentation, the sketch models can help the students communicate their concepts with 3D representations of their concepts. There are various milestones that follow sketch modeling to further develop and refine concepts but for this paper the focus is on design process leading up to and including sketch modeling.
2. Introduction to Sketch Modeling

Prototyping is utilized throughout the design process as a form of problem solving[4]. It is a “design method that uses physical prototypes to study and test how a new product will be used, and how it will look and be manufactured”[5]. The fidelity of a prototype can range from soft model 3D version of a sketch to a test of a manufacturing process to produce the final product. In 2.009 the term “sketch model” is used to refer to early stage physical models that are easy to make and made of soft, low-cost materials. Analytical models, typically referred to as estimations, are analogous to physical sketch models in fidelity. The sketch modeling assignment is the first time students are asked to create physical models at a time when the teams of around 10 students are exploring a set of three concepts from the brainstorming and concept selection exercises.

For most students the sketch modeling process is brand new and the purpose of a prototype this early in the design process can be unclear. Most concepts at this stage are product visions that have addressed a user need but the physical form is ambiguous and unknown. For this reason creating a physical model can feel premature. Unsure about how to make a physical model purposeful at this early stage, students focus on the sketch models as a class assignment and not a learning tool. This leads many students to jump straight into building a model without careful consideration of what or why they are prototyping. Students tend to justify their models after they have built them when the purpose of their model should be clearly defined before they even start to build[6].

To address the difficulty with which 2.009 students arrive at effective sketch models, this framework walks through the process of arriving at a sketch model from an initial concept. The framework is split into two parts to first arrive at an appropriate learning objective for the sketch
model and then to help realize the physical model. In formulating the learning objective, critical areas of concern for concept validation are introduced and physical components of the product vision are explored to find various potential learning outcomes of a sketch model. The first part of the framework ends by guiding students through prioritizing the different learning outcomes to arrive at a single target question for the sketch model. In the second section of the framework, examples are used to show students sketch models that targeted questions related to the same physical area of emphasis as their own learning objectives. This framework helps students create effective sketch models by outlining a sequence of actionable steps to encourage the application of design concepts throughout the sketch modeling process.

3. A Framework

A sketch modeling framework, meant to help students go from a concept or product vision to a useful sketch model, is split into two parts. This section will walk through the steps of arriving at an effective sketch model, introducing the relevant key concepts in the design process. In the first part, students are guided through a set of steps to help them arrive at a target question based on concerns for concept validation and physical exploration of the concept. This target question is meant to clearly define the learning objectives of a sketch model. With an articulated objective question, the second part of the framework guides students through examples to illustrate how to arrive at a physical model from the question defined in part one. The two parts are outlined below to illustrate the sequence of steps that lead to a strategic learning objective and the resulting sketch model.
Step 1: Arriving at a target question

Concept

Uncertainty
What does your design team not know about the concept?

Feasibility
- The existence and application of necessary technology
- Physical principles and mechanism feasibility

Market
- The existence and size of relevant markets
- Target customer interest

Customer Need
- What are the customer needs
- Are target customer needs met by product concept

Scope
- Time and resources necessary to make an alpha prototype
- Skills and expertise of team members

Physical Emphasis
What questions can we ask?

Form
Scale
Visualization
Usability
Interaction
Experience
Operational Principles
System Configuration
Integration

Prioritize
How does one choose which question to answer with the model?

This is a set of criteria to help students prioritize and strategically choose which question to answer in their sketch model.

Level of uncertainty in:
- Modeling
- Conceptual
- Team Skills
- Critical to concept validation
- Learning Outcome

Target Question

Step 2: Arriving at a sketch model

Target Question

Physical Categories
What type of question is it?

Form
Scale
Visualization
Usability
Interaction
Experience
Operational Principles
System Configuration
Integration

Model Types
Based on the design team's target question, the type of model is decided. "Looks Like" "Works Like"

Examples

Figure 1: Flow diagram outlining the steps of sketch modeling framework. Part 1 walks from a concept to a target question for a sketch model. Part 2 uses examples with similar learning objectives to help students create an effective sketch model.
3.1 Part 1: Arriving at a “Right” Question

3.1.1 Characterizing Uncertainty

As sketch modeling is meant to explore a concept to test its viability as a product proposition, the first step in formulating the target question is to determine what the design team does not know about the concept. In other words, the design team needs to address the different areas of uncertainty in their product concept to understand why they are making a sketch model. To clearly enumerate the relevant uncertainty at this stage of the design process the team should target four main areas of concern related to concept validation: feasibility, customer need, market, and scope. These four areas of consideration are not necessarily correlated to questions that can be developed into sketch models but are general key consideration in early concept development and selection. Considering all four concerns for concept validation will help the design team identify key areas of uncertainty to clarify why a sketch model is being made and where they hope to eliminate uncertainty in their concept.

**Feasibility**

Feasibility as an area of consideration in concept validation focuses on the necessary technology, engineering, and physical principles for concept validation. In the product design setting design teams often have concepts that rely on an alternative application of an existing technology. In this case a major concern is the existence of the necessary technology as well as its integration into the concept application. Similarly, if a concept relies on a mechanism or physical law the team is uncertain about, exploring the feasibility of this aspect of the product
might be a focus for the sketch modeling process. Example areas of consideration regarding the feasibility of a concept are:

- The existence and application of necessary technology
- Physical principles and mechanism feasibility

**Market**

The class is designed in a way to give students an idea of what being on a design team in a product development firm feels like and therefore places an emphasis on the financial and market viability of the products of each team. Through the concept selection process students are encouraged to consider market size and other financial considerations when evaluating different concepts. In an ideal case, the design team has done a sufficient amount of research before reaching the sketch modeling phase to have a baseline confidence in the potential markets for the concept. However, different concepts are introduced, or progress at different rates, and it is still very possible that a design team has many unknowns about their target market(s). In this case students may have questions about what the potential markets are, size of the market, target customer interest, and how much a customer might be willing to pay for the product. Example areas of consideration regarding the market of a concept:

- The existence and size of relevant markets
- Target customer interest

**Scope**

Scope as an area of concern targets the major limiting factors in making a product viable.

As mentioned above, the 2.009 experience is meant to emulate the experience in a product
design firm so design teams are provided with a budget they cannot exceed. Students will also consider the requirements to make an alpha prototype of the proposed concept, by considering the materials and machinery available in Pappalardo (2.009 prototyping shop) and in other shops at MIT. There is also a limitation set by team knowledge and ability. However, before students discard a concept due to lack of ability on the team they should consult machine shop staff and class mentors who may be able to provide the necessary instruction and ideas about alternative manufacturing methods. Example areas of consideration regarding the scope of a concept:

- Time and resources necessary to make an alpha prototype
- Skills and expertise of team members

**Customer Need**

In user-centered design emphasized in the class means concept identification centers around finding or identifying a user need. For this reason, uncertainty around user needs can be crucial to explore and identify early in the design process. As concepts progress, hidden or secondary user needs might be discovered. It may also be the case that the product does not address or solve the user need as expected. If there isn’t clarity in the connection between the team’s concept and a user need it might be helpful for the design team to develop a clear understanding of the user needs. Clearly defining the customer needs and having a clear connection to the design teams concept will help validate the concept and justify product specifications based on the user need[7]. Example areas of consideration regarding the customer needs related to a concept:

- What are the customer needs
- Are target customer needs met by product concept
After honing in on one of these four main areas of concern: market, feasibility, scope or customer need, it will not always be the case that a model is the best way to address the uncertainty. Often times the best way to address some of these areas of concern are through other methods such as field research, customer interviews or analytical calculations. Concerns regarding feasibility and the functionality aspects of customer needs are generally those that tend towards physical models as they directly impact the physical form of the product. Scope, market and investigation of customer needs can often be explored with various forms of research and other types of modeling. These are generalizations of more specific areas of concern for each design team. There are certainty instances where physical models can addresses any of the four key concerns for concept validation. For instance, if the design team would like to gauge customer interest for market research, they may choose to create a prototype for testing on potential users.

3.1.2 Physical Areas of Emphasis

The first step in this framework, where students are encouraged to brainstorm and outline everything they don’t know about their concept, are not be guided by the expectation that they will make a physical model. In this step of the framework a more specific question will be framed that address the area of uncertainty identified above and hone in on a more specific aspects of the concept that can be realized physically. Areas of physical emphasis have been split into three categories: appearance, user experience and functionality.
Appearance

The three areas of emphasis in appearance are: form, scale and visualization. Sometimes referred to as the “form factor”, form can refer to any variation on the physical form of the product concept. _Is it a type of wearable or hand-held device? Does it need one, two or no hands for operation?_ At this stage, design teams should not be attached to one physical form of their concept as it is likely that there are various potential form factors. For some design teams, early concept exploration may involve identifying the form factor best suited for meeting the customer’s needs. Similar to the form of the concept, scale relates to an exploration of what contextual factors best address the user need. _How large should it be in relationship to its users or physical context? Can the user hold it in one hand or is it too big to pick up?_ Form and scale questions address the feel, haptic experience and physical interaction of the user with the product. Other visual details can be explored such as material, color, industrial design, and surface finish. Visual details can contribute to the feel and experience of the product as well serve as visual cues that that guide the user.

User Experience

Questions around the user experience look more in depth at how someone uses and physically engages with the product while considering usability, interaction and experience. A product can function as intended but not be usable due to poor design features that don’t communicate the functional steps to the user. Usability targets the users understanding of how the product works. _Are they able to use it without additional instruction? Is using it efficient and fast enough for the desired function? Does the user get confused or frustrated?_ Exploration of the interaction takes a closer look at how the product receives an input from the user and how
they receive feedback from the product. Looking at the user experience can examine the emotional and community aspects of the concept. *Is the product fun to use? Does it illicit an intended emotional response?* Does it promote or discourage interaction with others?

**Functionality**

Emphasis on functionality generally answers the question: *How does it work?* This can mean looking at operational principles, system configuration or integration. Key features of the product may rely on a mechanism or physical action that can be tested and explored as one of the concepts key operational principles. Sometimes a design team needs to look at these principles in isolation to achieve a level of confidence or understanding in how the individual principles function. Other areas of functional concern can deal with how a part interacts with a complete system configuration. System configuration and integration often play key roles in concepts requiring electronic forms of control and communication between individually functioning parts.

### 3.1.3 Prioritizing

As sketch modeling occurs early in the design phase, students are often working with multiple concepts that still remain fairly undeveloped. Consequently, as students address the areas of uncertainty in their concept and then focus on more physical aspects of their product vision, they will most likely develop several questions that lend themselves to being solved with physical sketch models. The last section of the first part in this framework is meant to help students prioritize and strategically decide on what question to answer in their prototype.
Students are first encouraged to execute an initial filtering of the question they developed in Part 1. As the focus of sketch modeling is concept validation, the first step is to rank the questions based on criticalness to concept validation. The rankings should focus on the key concerns mentioned above: market, feasibility, scope and customer need. Based on the rankings, the design teams can select the four or five most critical questions. This allows the design team to narrow their focus on fewer questions to be discussed further in the remaining prioritization considerations.

The process of prioritization mimics that of the concept selection method developed by Stuart Pugh in the 1990’s[8]. Using this method, a Pugh chart or matrix is created with selection criteria on one axis and concepts on the other. One reference concept is chosen and the rest assigned a (+), (-) or (0) to represent “better than”, “worse than”, or “same as” for each criterion in comparison to the reference concept. Finally the scores are summed and used to rank the various concept and assist in deciding between concepts, combining them, or modifying to improve.

For the purpose of deciding between target questions for a sketch model, the concepts are replaced with potential questions and the concept selection criteria with prioritization criteria. While the design team can add any prioritization criteria they see fit, those suggested for this framework are level of uncertainty, criticalness to concept validation, and learning potential.

The uncertainty criterion asks: *How uncertain is the design team of the answer to this question?* Three major concerns relating to uncertainty of the question are modeling, conceptual, and team skills. Modeling uncertainty is concerned with the ability to create the necessary model to answer the question. This may be an issue for reasons related to time, difficulty, materials, or other available resources. Conceptually, the team may be very uncertain of the answer to the
question or what the answer will even look like. This is often the case in these early stage exploration phases when concepts are early and undeveloped. Finally, a design team may be uncertain or very certain of their ability to create a model to answer the question. This point is particularly important in the context of 2.009 as it is not uncommon to see student teams create a model because they know they have the skill set to create the model and not for the purpose of a learning outcome. As students become distracted by the assignment of having to create a physical model, they end up justifying a learning outcome after the fact. This leads to a situation where concept development can be limited. Conversely, a team may be uncertain on if they have the skill set to answer a question such as specific modeling, electronics, or knowledge set.

Different question will be critical at different stages of the design process. For a sketch model, answering a question like “does the principle mechanism work?” versus “what color should it be?” is much more critical for concept validation. Different questions may also have varying levels of learning potential. This can be difficult to predict as sketch models often lead to unexpected lessons but some questions lend themselves to potentially addressing various aspect of the concept. Using the same comparison of “Does the principle mechanism work?” versus “What color should it be”?, answering the first question will address operational principles but may also reveal issues relate to usability or the necessary interaction. Considering how critical a question is and considering the various forms of learning potential can help the design team pick the right question for the current design phase.

The following Pugh Chart is an example implementation of the prioritization criteria to assist in the selection of a target question. It is based on a 2.009 teams concept called Four Leaf, a product that assists in the “on the go” eating experience at a food truck. In this first concept iteration, the team explored the idea of a portable and flexible table that could be easily setup in
various locations by clamping to different types of objects. Based on the criteria, the question of how the table will clamp to various objects is prioritized above the rest. This question meets one of the key customer needs and has a fair amount of conceptual and modeling uncertainty that should be addressed earlier rather than later to validate the concept. The question of the ease of deployment of the table is also critical to the customer’s needs but can be explored after the clamping mechanism has been figured out. The shape and material of the table surface are both important factors in refining the user interaction and experience but are not critical to concept validation and there is little uncertainty in how to model and answer those questions conceptually.

<table>
<thead>
<tr>
<th>Prioritization Criteria</th>
<th>Questions</th>
<th>Uncertainty</th>
<th>Modeling</th>
<th>Conceptual</th>
<th>Team skills</th>
<th>Criticalness to validation</th>
<th>Learning potential</th>
<th>Sum +’s/-’s</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>How do you make the table easily deployable? (Reference)</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>What clamping mechanism will allow compatibility with different shaped objects?</td>
<td>+2</td>
<td>-4</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>What shape and how far should tables extend?</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>What material should be used for the table surfaces?</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-5</td>
<td>4</td>
</tr>
</tbody>
</table>

**Figure 2:** Example question prioritization Pugh Chart using the *Four Leaf* example concept. With this concept the design team wanted to create a portable table to enhance the “on the go” eating experience at food trucks[9].
The modified Pugh chart is meant to help organize the potential question and encourage discussion within the design team to consider the criteria of uncertainty, criticality and learning potential. The resulting score of the questions is not meant to choose the question for the team but rather to help them strategically pick a question that will lead to an effective sketch model.

3.2 Part 2: Make a Model to Answer the Question

The second part of the framework will help students plan a modeling strategy that will answer the question articulated in their learning objective. This is primarily achieved by providing examples of sketch models with similar learning objectives as that of the design team. The goal is not to provide sketch modeling techniques like using cardboard or blue foam but to give students an understanding of how a physical model can answer a question about the product concept through a set of examples demonstrating different types of models which address questions in different areas of physical emphasis.

3.2.1 Physical Categories

The examples can be most clearly organized initially by the physical areas of emphasis identified in the first part of the framework: appearance, user experience and functionality. The specific questions posed by the design team and those used in the examples will be specific to their associated product concepts and will never be exactly the same.
3.2.2 Model Types

At this stage it is useful to categorize sketch models into “looks like” and “works like” to focus the modeling process. Design teams should have a clear question they are trying to answer with their sketch model, making it clear what model type is not appropriate. Teams may consider the target question as well as how they plan on testing their sketch model to guide them toward either type of model.

“Looks Like”

This category of sketch model can have limited functionality but has a high fidelity appearance. Typically made out of wood or foam and painted these sketch models should focus on making the prototype appear like the concept. If necessary to answer target question, limited functionality may also be included. The audience for testing “looks like” models can be designers, a client, or potential customers. Testing these prototype does not always require physical interaction between the model and the audience and other forms of testing can be employed such as a survey with images or videos.

“Works like”

These models focus on functionality of the concept. In this case the design team should not focus on what the model looks like but instead ensure the functional fidelity of the prototype is adequate for testing. In the case of testing a mechanism, your audience might just be your design team or engineering consultants. Other audiences might include designers and potential customers in which case it is important to clarify the purpose of the prototype and make it clear it
is not the final product. It is also important to keep in mind that the final product will most likely not function exactly as the prototype depending on the quality of the prototyping materials versus the final materials. Testing “works like” models requires physical interaction and therefore cannot be completed remotely online.

Following are examples of both “looks like” and “works like” sketch models from past 2.009 teams and other product design classes at MIT. These examples highlight the design teams concept, objective questions and learning outcomes of their sketch models.

### 3.2.3 Example 1: Mason Frame

**Concept:** A device to assist workers in the repointing process by reducing fatigue, increasing accuracy and reducing noise and dust. Repointing is the process in which workers remove and replace the mortar between bricks every 20-30 years. With no specific tool for repointing, angle grinders are usually used and the design team wanted to create a device to assist in the repointing process. Initial sketch models explored the potential form factor of tool that held the angle grinder while being mounted on a horizontal and vertical axis to carry the weight of the tool and allow workers to more the tool more accurately.

**Question(s):** How usable are the vertical and horizontal axis for the workers? What is the best way to integrate the angle grinder into the tool?
Figure 3: Sketch models for Mason Frame, a device that helps workers in the repointing process by reducing fatigue and increasing accuracy. The sketch models questioned the usability of the vertical and horizontal axis on which the angle grinder is mounted as well as the integration of the angle grinder onto the device[10].

Lessons Learned: When testing the vertical and horizontal axis it was immediately apparent that jamming along the vertical axis was an issue restricting the workers movement. This version of the form factor also posed portability and weight issues as carrying around the two axis was neither easy nor convenient. Mounting of the angle grinder to the device revealed a key user need which was to be able to easily access the bit for easy removal and replacement[10].

3.2.4 Example 2: Four Leaf

Concept: A product to assist in the “on the go” eating experience at a food truck by creating more surfaces for customers to eat on. The team wanted to create a portable and flexible device that could be setup and used in various different locations. The form factor of the initial concept consisted of four panels that could be mounted to various cylindrical objects such as trees and lamp posts to create a table to eat on.
**Question(s):** What clamping mechanism will allow the table to be mounted on objects of various sizes and shapes?

![Figure 4: Sketch models for *Four Leaf*, a portable table to assist in the “on the go” eating experience at a food truck. The concept is to have a table that can be clamped or mounted to a variety of objects to provide eating surfaces. The sketch model explores a mechanism for clamping to cylindrical objects such as trees and lamp posts[11]](image)

**Lessons Learned:** The clamping mechanism proposed in their sketch model was limited to cylindrical objects between diameters of 5” and 20”. In testing the model the design team was able to identify customer needs such as increased load capacity, ease of deployment and the customers desire to have an eco-friendly product. In this case, a sketch model that initiated as a feasibility test, exploring the operational principles of the clamping mechanisms, became a tool to identify unknown customer needs and specifications.

**3.2.5 Example 3: Piece by Piece**

**Concept:** The design team was tasked with creating a life sized puzzle that can fit in a 200 square foot room. They chose a chocolate theme and wanted to create a themed, larger version of the 2D sliding piece puzzles.
**Question(s):** What scale should the pieces be to fit in the room and encourage players to push them around? What designs should be on the pieces?

![Image of chocolate pieces](image1.jpg)

**Figure 5:** Sketch models for *Piece by Piece*, a life-sized puzzle in which human scaled pieces are arranged to achieve different patterns in the chocolate themed decorations. The sketch models addressed the scale of the individual pieces to achieve the desired interaction where players push the pieces around to solve the puzzle[12].

**Lessons Learned:** The 1:12 scale model made each chocolate piece 3x3x2.5ft allowing the entire grid to fit in room size constraints. With the pieces falling around waist level of the players they are encouraged to push and slide the pieces against the ground instead of pick them up. Revealed from an experiential level, the solution added excitement from the physicality of having to push around 3D pieces to solve the puzzle.

The *Mason Frame* and *Four Leaf* sketch models are examples of “works like” and *Piece by Piece* of a “looks like” model that addressed questions related to physical areas of emphasis outlined in the framework. *Mason Frame* model explored the usability and integration of their conceptual form factor while *Four Leaf* tested an operational principle key to the validation of their concept. The *Piece by Piece* model defined scale and the experience of their concept. The
questions asked by the design team are specific to their concept but they along with the learning outcomes of the models can be categorized into the areas of physical exploration.

4.0 Guide For Student Use

This section will walk through a typical scenario in the 2.009 class setting illustrating how the steps in the framework would help a student arrive at a sketch model. We begin right before the sketch modeling phase when teams have broken up into smaller groups of three to four students to explore and validate their most promising concepts. One example is a team that has identified potential in a product that assists firefighters detect thermal dangers behind closed doors. Current methods involve firefighters removing their protective gloves, testing the temperature of metal door knobs with the back of their hands and guessing the likelihood of a fire behind the door based on the temperature of the door knob. The team sees potential in improving this method and explores the idea of a device that helps firefighters determine if there is a fire behind the door more reliably and safely. To do so, the team would follow the key considerations outlined in the sketch modeling framework.
Step 1: Arriving at a target question

Concept

Uncertainty
What does your design team not know about the concept?

Feasibility
The existence and application of necessary technology
Physical principles and mechanism feasibility

Market
The existence and size of relevant markets
Target customer interest

Customer Need
What are the customer needs
Are target customer needs met by product concept

Scope
Time and resources necessary to make an alpha prototype
Skills and expertise of team members

Physical Emphasis
What questions can we ask?

Form
Usability
Operational Principles

Scale
Interaction
System Configuration

Visualization
Experience
Integration

Prioritize
How does one choose which question to answer with the model?

This is a set of criterion to help students prioritize and strategically choose which question to answer in their sketch model.

Level of uncertainty in:
Modeling
Conceptual
Team Skills
Critical to concept validation
Learning Outcome

Target Question

Figure 6: Flow diagram outlining the first step of the sketch modeling framework. Part 1 walks from a concept to a target question for a sketch model.

Following Part 1 of the framework the design team first considers the four areas of uncertainty related to concept validation. In this case the relevant market is straight-forward but the cost and sale price could affect how willing fire departments are to purchase the device. In terms of feasibility, the team might have questions about temperature sensing devices and the necessary range to measure temperatures of the hot door knob. In order to ensure the device meets the user need, the concept needs to improve upon the existing method for detecting fire behind closed doors. For these considerations the team would want to know how to reliably and
quickly measure the temperature of a door knob and how those temperatures correlate to thermal dangers like fires and smoke behind closed doors. Finally, for the scope of the project the design team might consider having some knowledge in thermodynamics which is likely considering the class consists of mostly mechanical engineering students. After walking through these four areas of uncertainty the team identifies the exploration of customer need as the focus of their sketch model. Design team members may have research or knowledge that lead them to believe the market and feasibility are of less concern.

Next, the students walk through the physical areas of emphasis as a guide in forming questions about their concept. For the fire detection device some of these questions might be:

**Appearance**

*Is the device a wearable that attaches to the person?*
*Is it one contained device or does it have multiple parts?*
*Does it attach to the belt or helmet of the firefighter?*
*How large of a device are firemen willing to add to their gear?*
*Should the device match the design of other firefighter gear?*

**User Experience**

*What form factor is most intuitive for firefighters?*
*How does the device communicate to the firefighter the temperature of the door?*
*How does the device signal to the user if there is a fire or not?*
*What types of feedback should be used?*
*Will LED’s be visible through the smoke in a room with a fire?*
*Are vibrations easily felt through the jackets and protective wear of firefighters?*
*Is the added device uncomfortable or inconvenient to wear?*
*Do different types of door knobs affect the device sensing interface?*

**Functionality**

*What temperature sensors give the right range for temperatures of the door knob?*
*Can sensors read temperatures fast and reliably enough to be useful to firefighters?*
*What material should the temperature probe be made out of to allow for durability?*
What material should the temperature probe be made out of to allow for fast and reliable temperature readings?
What temperature ranges indicate a fire or other types of thermal danger?
How does the sensor fit into the device?
What material should the housing be made of?

To decide on the target question for the Sketch Model the team walks through the prioritization process. The first step is ranking the questions based on how critical they are to validating their concept. Without ranking the entire list of questions, one can imagine this would allow the students to narrow down the list to four or five critical questions:

- How does the device signal to the firefighter if there is a fire or not?
- Is the device a wearable that attached to the person?
- Can sensors read temperatures fast and reliably enough to be useful to firefighters?
- What temperature ranges indicate a fire or other types of thermal danger?

Then, discussion of the prioritization criteria with the aid of a Pugh Chart would allow the students to form and initial ranking of the narrowed list of questions. Through discussion of the uncertainty, criticalness to concept validation and learning potential of the four questions the team can pick the learning objective most suited for the sketch modeling phase in which concept exploration and validation are the main goals. In this example the team would most likely choose “Can sensors read temperatures fast and reliably enough to be useful to firefighters?”. This question will address the key customer need in improving upon the existing method and begin to identify requirements for the temperature sensor and probe.
### Questions

<table>
<thead>
<tr>
<th>Prioritization Criteria</th>
<th>How does the device signal to the firefighter if there is a fire or not? (Reference)</th>
<th>Is the device a wearable that attaches to the person?</th>
<th>Can sensors read temperatures fast and reliably enough to be useful to firefighters?</th>
<th>What temperature ranges indicate a fire or other types of thermal danger?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modeling</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Conceptual</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Team skills</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Criticalness to validation</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Learning potential</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Sum +'/-&quot;s</td>
<td>0</td>
<td>+4</td>
<td>+5</td>
<td>0</td>
</tr>
<tr>
<td>Rank</td>
<td>3/4</td>
<td>2</td>
<td>1</td>
<td>3/4</td>
</tr>
</tbody>
</table>

**Figure 7:** Example question prioritization Pugh Chart for the fire sensing behind closed doors concept. After ranking all potential questions based on criticalness to concept validation, the top four questions are compared using the criterion: uncertainty, criticalness to validation and learning potential.

**Step 2: Arriving at a sketch model**

**Target Question**

**Physical Categories**

What type of question is it?

- Form
- Scale
- Visualization

- Usability
- Interaction
- Experience

- Operational Principles
- System Configuration
- Integration

**Model Types**

Based on the design teams target question, the type of model is decided.

- "Looks Like"
- "Works Like"

**Examples**

**Figure 8:** Flow diagram outlining the second step of the sketch modeling framework. Part 2 uses examples with similar learning objectives to help students create an effective sketch model.
They will first consider the physical area of emphasis they have chosen with the question “Can sensors read temperatures fast and reliably enough to be useful to firefighters?”. The main emphasis is on the crucial operational principle for the concept, its ability to meet the user’s need of measuring the door knob’s temperature quickly and reliably. The model will most like focus on the sensors and temperature probe as they are central to the functionality but may also assume a potential form factor whether that be a wrist band, belt attachment, or other device. In this case the sketch model and the testing of the model may also explore the form of the fire detection device and how the firefighters interact with the device and the door knob.

Given the learning objective, this design team requires a “works like” model to test the temperature sensing mechanism. The team would then proceed to explore sketch model examples that are both “works like” models and answered questions relating to operational principles of a product concept. At this point the design team, with a clear objective question and example sketch models as a reference, can design and build a sketch model to answer their question and advance their understanding of what a device that helps firefighters detect fires behind closed doors requires to be successful.

5.0 Conclusion

In this paper a framework is outlined that will guide 2.009 students through a set of steps to apply key design concepts that will help students better understand the purpose of sketch modeling. The steps will lead students to strategically formulate their own learning objectives in order to design effective prototypes that advance their product concepts.

The first portion of the framework and sketch modeling process focuses on identifying a learning objective in the form of a question that can be answered by the sketch model. As this is
part of the concept validation phase, the design teams are first encouraged to consider four key areas of concern in concept validation: feasibility, customer need, market and scope. This first step does not develop physical models but encourages the team to identify all areas of uncertainty regardless of whether addressing the uncertainty would require a physical model or not. Then with general uncertainties identified physical areas of emphasis are explored to clearly articulate objective questions that can be answered with a sketch model. The appearance, user experience and functionality of a concept are all considered. Finally, a question selection process based on a Pugh Chart is proposed to help students consider level of uncertainty, criticalness to concept validation and learning potential to strategically choose a single objective question that will lead to the most effective sketch model for the concept validation and selection phase of the design process.

The second portion proposes using examples to guide students from their learning questions to a physical model. The areas of physical emphasis: appearance, user experience and functionality and the more focused areas such as usability, scale or operational principles, are used to group sketch model examples with similar learning objectives. Another level of categorization is added to separate “looks like” and “works like” sketch models to see how the two different types of models answer learning questions. Once students have chosen a learning objective from part 1 of the framework, they are encouraged to consider the two different types of models and which will better answer their target question. Finally, categorized as “looks like” and “works like” and by their physical area of emphasis, students will be provided with a sketch model example(s) that had learning objectives similar to that of the design team.

Three examples, two “works like” and one “looks like” are provided in the paper. Next steps in the project would include building the database of sketch model examples from past
2.009 projects and other relevant product design examples. As seen in the examples in the paper, some sketch models address multiple areas of physical emphasis, and could be cross referenced showing the concept of learning potential mentioned in the prioritization section of Part 1. With the collection of examples a student would be able to identify their physical area of emphasis, what kind of model they are planning to make and see various examples to show how other design teams have tackled similar questions with a physical model.

This two-part framework is developed with the intention of helping 2.009 students build effective sketch models that serve as learning tools in the design process. The next step of this project would be to create an online learning tool, including the sketch modeling example database, based on the framework that can be utilized by the students as they work through the sketch modeling milestone. With limited lecture time mostly focused on physical soft modeling tools, an online tool can provide additional conceptual understanding of the purpose of sketch molding as well as guidance tool that helps the design teams formulate questions and design effective models.

The next step to make the sketch modeling framework useful to 2.009 students will be implementation of an online tool outlined by the steps discussed in this paper. The online resource will guide students step by step to arrive at their target learning objective and then their model. Part of this resources will require a database of sketch model examples complied from past 2.009 projects as well as other product design classes and resources at MIT. This database will be organized by the physical areas of emphasis and type of model, “works like” or “looks like”, of the different examples allowing students to explore models similar to those they need to build for their concept exploration.
6.0 References


