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EVALUATION OF SYSTEMATIC DESIGN METHODS USED IN SENIOR DESIGN PROJECTS

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ABSTRACT
System Engineering (SE) is utilized in structuring a product development process into simple and collaborative activities, while at the same time, supporting engineers' decision-making. In most undergraduate engineering design courses, SE was taught by assigning industrial-like projects in which teams of students developed products using certain design methods while following structured design process. It has been observed that some design methods were adopted naturally and used effectively by students while some are less preferred. This is due to various reasons, from strict project deadlines to the fact that some methods are difficult to understand. In this paper, we studied these design methods in the context of senior design projects. We have observed students' applications of these methods and conducted surveys to assess whether they believe these methods helped their design activities. This study will help us understand how to help students gain knowledge in product development through project-based learning, as well as provide some insights on how inexperienced engineers may use various design methods.

Key Words: Design, Education, System Engineering, Senior Design Project

1. INTRODUCTION
Design theory and methodology (DTM) is a collection of "understandings and findings" in the fields of design process modeling, design activities management, methodologies to achieve design goals, and methods of creating innovative solutions to design related problems. In the last two decades, due to the increasing complexity of commercial products, it has been observed that a significant gap exists between the industry applications and engineering education of DTM, also called design education. That is, although widely taught in the classroom, DTM has mostly been seen with much less industry application. The reasons are, as Tomiyama et. al [1] pointed out, DTMs "do not emphasize innovative design, and they are not useful for routine design or improvement design which is the majority in industry". However, "(design) process technologies are widely taught and used". In this paper, our study is primarily focused on teaching System Engineering (SE) as a "process technology" in engineering design.

SE is a multidisciplinary approach for the design, management, and realization of a complex system. In the area of product development, SE is utilized in structuring a product development process into simple and collaborative activities in the product lifecycle; while at the same time, supporting engineers' decision-making. The concepts of SE are widely used in industry applications and design education, in which students without product development experience need to learn how to organize the activities in product development process, how to manage information and knowledge flow, how to strive for innovation, and how to deliver concrete solutions while compromising conflicting customer requirements. SE is suitable for this purpose, especially at the early stages of product development, when a lot of uncertainties and a lot less knowledge exists in the design problem.

SE provides high level systematic management methodologies for design activities, as well as specific design methods for generating concrete solutions at early stages of product development. Examples of SE methodologies in product design are Pahl & Beitz's Systematic Design [2], and Ullman's Mechanical Design Process [3]. SE design methods for concrete solutions include Quality Function Deployment [4], Morphological Chart [5], Decision Matrix, Function Structure, etc. In our Senior Design class, we adopted the product development process presented in Ulrich and Eppinger's textbook [6] due to its simplicity and efficiency in design education. A similar SE process is also presented in [7].

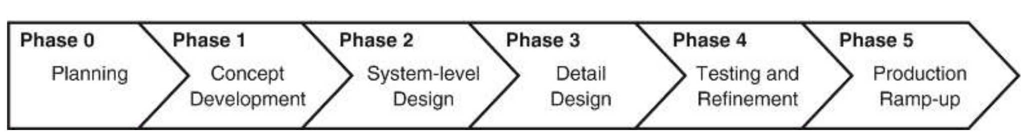


Figure 1. Ulrich and Eppinger's Product Development Process

Ulrich and Eppinger's product development process is a linear iterative process, as shown in Figure 1, in which a product is developed through five phases after planning and approval of the project. In Phase 1, the concept development phase, market research is conducted to collect information about customer requirements. The functions/subfunctions of the designed product are analyzed using Function Structure, also called Classification Tree. Product developers find solutions to the subfunctions and combined them into a set of design concepts using Morphological Chart, also called Combination Table in Ulrich and Eppinger's textbook [6]. Then Decision Matrix is used to compare and select design concepts. Finally, preliminary design specifications are determined using Quality Function Deployment (QFD). In Phase 2, the system level design phase, product developers organize product components into "chunks", and create CAD model considering the spatial layout of the components and chunks. In Phase 3, the detailed design phase, the CAD model is refined based on engineering specifications such as material selection, components selection, connections mechanisms, kinematic movements, mechanics and thermal performances, manufacturing considerations, etc. At this stage, prototypes can be built to test the design concept. After the detailed CAD model is finalized, Failure Model and Effect Analysis (FMEA) is carried out to ensure the safety of the design. Finally, in Phase 4 Testing and Refinement phase, and Phase 5, Production phase, more detailed design prototypes will be built and tested. Product design and relevant technical documents such as drawings, manufacturing process, packaging, and delivery, etc. will eventually be approved.

In our senior design courses, students completed team-based product development projects following Ulrich and Eppinger's design process. Students' work was documented, including the timeline, the design methods they used, decisions they made, etc. The following are five design methods that are used in all these senior design projects. Some other product specific tools such as CAD, FEA, etc. are not discussed because our focus is on evaluating SE design methods.

- Function Structure (Classification Tree)
- Morphological Chart (Combination Table)
- Decision Matrix
- QFD
- FMEA

During the projects, we observed students' acceptance and use of these design methods, as well as their decisions. This observation can help improve design education to engineering students and provide some insights on managing teamworking activities and training unexperienced engineers in product development. We also surveyed the students by asking them the following questions:

- Did you have faith in the method and willingly use it?
- Did you apply the method independently without making conceptual mistakes?
- Did you make appropriate decisions using the method?

In the following sections, a recent senior design project is presented. Its product development process and decision-making activities are discussed in detail. Students' assessment and preferences when using these design methods are discussed and summarized.

2. CARRYBUDDY PROJECT

In this project students proposed to develop an autonomous human-following robot container called CarryBuddy. The container can hold a carry-on luggage and follow its user autonomously. It will be used mostly indoors such as in the airport but should also be able to go over small obstacles such as a road curb. CarryBuddy will be controlled by an Arduino Mega micro-controller and a Raspberry Pi 3 microcomputer.

Students accomplished the project following the process as shown in Figure 1. This is a very straightforward and almost *ad hoc* process, hence why students are always willing to follow it. When working on multidisciplinary product development projects, though, we have noticed that most students lack teamwork skills, especially at the beginning of a brand-new project. They are usually reluctant to make any decisions when very little is known about the project and tend to discuss everything in one large group. These lengthy discussions can take several weeks and are often unfruitful. If given clear instructions about the topics, they became more focused and moved the project forward relatively efficiently. We believe it is okay for students to work in a large group at this stage, but it is also important to remind students that most decisions made at this stage are not final, and they can change them in the later stages. The topics that we suggested for students to discuss are:

- Identifying customer requirements and needs, including market needs, product functions, cost, service environment, manufacturing requirements, safety and environmental regulations, and product liability.
- Bench marking of the similar products in the market.
- Discussing the key tasks, milestones and timeline of the project.
- Discussing the team structure and resource management plan which will be implemented to complete the project.

Students conducted online market research of similar products and interviewed potential customers among their friends and family members. They concluded a set of customer requirements as following:

- overall size is less than 22 inch x 17 inch x 15 inch
- spacious enough to store a standard carry-on luggage
- can move freely with up to 30 pounds of load
- has autonomous human following capability
- can detect obstacles. Stop in front of obstacles higher than 6 inches and drive over ones lower than 6 inches
- budget friendly
- lightweight

2.1 Phase 1: Concept Development

After deciding the customer requirements, students created a function structure, in which the product's function is partitioned into simpler sub-functions so that each one can be provided using one part or component. The function structure is also called the Partition Tree. Its purpose is to decompose a complex product development problem into simpler sub-problems which can be solved separately. Different engineering teams may generate different function structures. As shown in Figure 2, students created a simple function structure for CarryBuddy. It has three major functions: storing, moving, and following. Storing items can easily be done using a robot chassis. Moving function is decomposed into subfunctions of navigation and obstacle detection. Navigation function is enabled using a motor driver board to control the motors on the chassis. Obstacle detection involves a camera and an ultrasonic distance sensor that detect the height and distance of an obstacle in order to decide either to stop or try to drive over the obstacle. Human tracking and following is accomplished by the camera, which is programmed using OpenCV and Python.

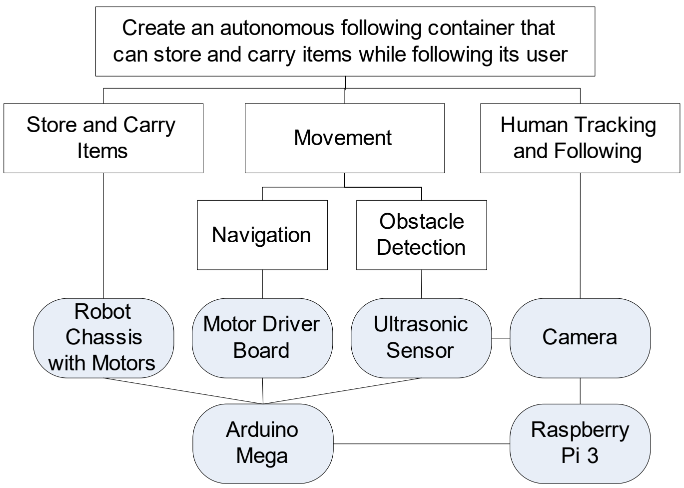


Figure 2. Function Structure of CarryBuddy

Function structure is a design method that can be easily understood and applied by students. It is also an effective communication tool for team members to analyze a product and find innovative solutions collaboratively. In order to deliver concrete solutions in this early phase, students must fully understand the design problem. We have observed that some students tend to stick to the first idea that they like and create the function structure for that idea, instead of using the design method to explore new ideas. We believe function structure is more effective as a teamworking tool than a design method. It can guide students through the planning process of the following tasks and deciding their team structure. In this project, ten students formed three teams: the kart team, control team, and powertrain team. The kart team designed and built the structure of the CarryBuddy. Control team was responsible to the electrical components, i.e. the battery, the control circuit and coding. The powertrain team designed and built the mechanism that transmits power from the electrical motor to the driving shaft. We have observed that students were able to make significant progress once they went beyond this stage of product development. It is unnecessary to require students to create a very detailed function structure. Being able to decompose the project into activities and tasks, as well as being able to assign clearly defined tasks to different teams seems more important.

We surveyed students in the last five years using the three research questions given at end of Section 1. The result is shown in Figure 3. Function structure is a simple method, since the students have no problem using it in product development and the results are usually appropriate.

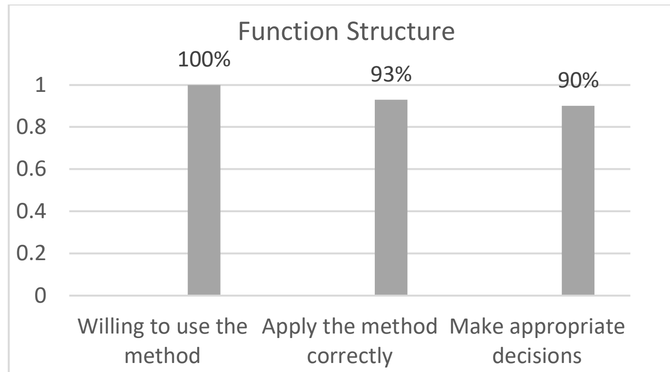


Figure 3. Evaluation of Function Structure

The next activity in the process is to select components and parts as solutions to the sub-functions and generate design concepts using morphological chart. Then, the most promising design concept is selected using decision matrix. This stage requires extensive knowledge and experience from students. As shown at lower part of Figure 2, each part or component of Carrybuddy corresponds a subfunction. In each design concept, these parts and components are organized into subassemblies and combined into different architectures. Students spent a lot of time googling and reading papers to develop the most successful design concepts. Some initial design concepts are shown in Figure 4.

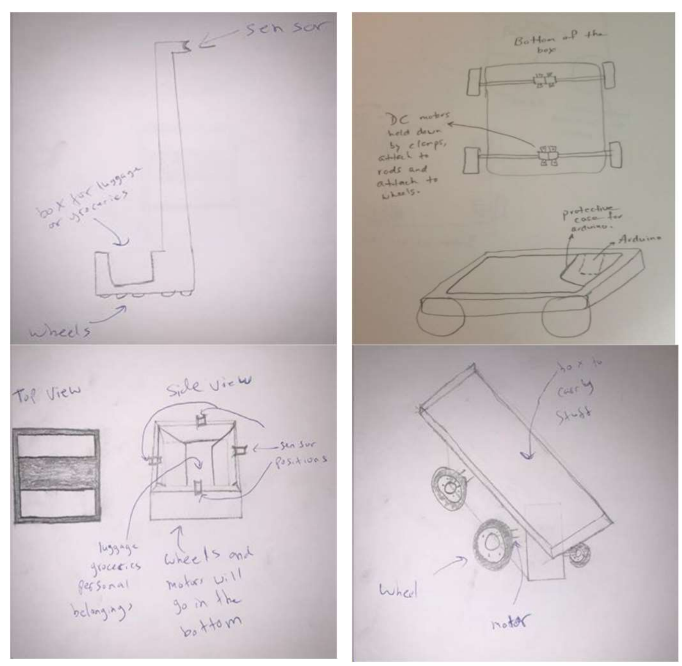


Figure 4. Preliminary Design Concepts

Morphological chart, also known as Combination Table, is easy to understand but difficult to use because it requires a lot of time to investigate and search for solutions. Usually, students focus on one idea that they like and are unwilling to explore alternative ideas. The survey results in Figure 5 clearly show that the morphological chart is a challenging design method for students because many of them think the exploration process is "a waste of time".

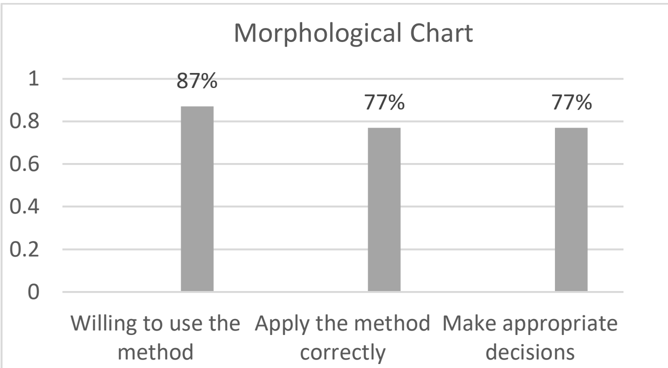


Figure 5. Evaluation of Morphological Chart

The following activity is to compare and select design concepts using decision matrix. Decision matrix is easily understandable. However, we found that it does not work well in our senior design projects. The key of successfully applying this design method is to develop design concepts to the extent that they can be meaningfully evaluated and compared. Since each design concept is scored using weighted addition of ratings w.r.t. a set of criteria, it is necessary to collect a large amount of data in order to derive meaningful ratings. For example, one of the criteria of the project is that the product has to be light weight. In order to compare the weights of different design, each of these design concepts must be develop so that its weight can be reasonably estimated. In ideal cases, prototypes should be created, measured, and compared, which is unrealistic in both senior design projects and most industry projects. Therefore, when being used to choose early-stage design concepts, it is important to choose several design concepts for future development. We also believe it is necessary to re-evaluate all the decision matrixes in the later stages of product development, after the product is fully developed. That is, the decision matrix should be used not only for concept generation at early stages of product development, but also for design concept validation in later stages.

A student survey of decision matrix is shown in Figure 6. It can be seen that students are willing to used it but sometimes may use this design method incorrectly. The major reason is the lack of details in the design concepts, which can attribute to the limited time available for student to complete the senior design projects.

2.2 Phase 2: System Level Design

The following activity is to construct a Quality Function Deployment chart to map customer requirements into design specifications, as shown in Figure 7. Θ represents strong relevant relationship between a customer requirement (row) and a design specification (column), ○ represents a moderate relationship, and ▲ means no relationship. For instance, the customer requirement of low operating noise is strongly related to the DC motor chosen and the speed limit of the product, so it is shown with Θ on the chart. It is not related to other engineering specifications such as the GPS installed on the CarryBuddy, or the size of the compartment, so it is shown with ▲. QFD is used to check the customer requirements to ensure none is ignored, and check design specifications so that any engineering work done will always contribute to the quality of the product. Any design specification that has a lot of strong relationships with customer requirements should receive a lot of attention from engineers. Moreover, QFD is very effective when an engineering team decides the specified goals and target values of the design specifications.

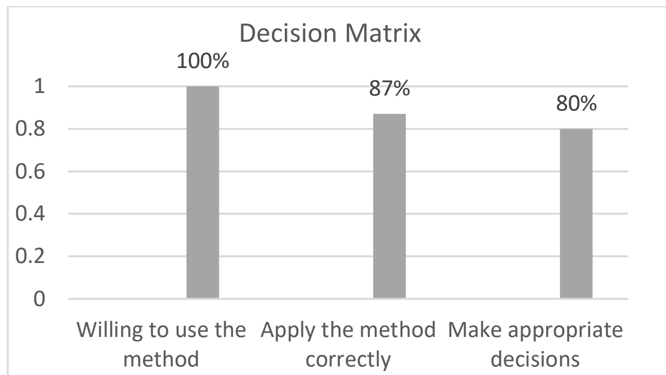
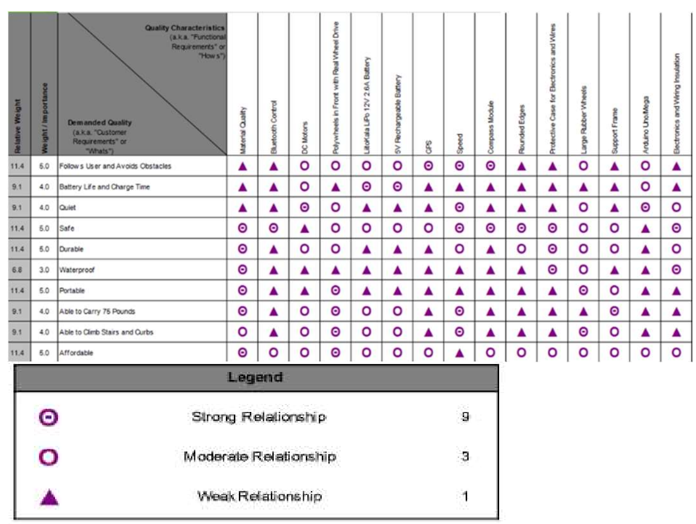


Figure 6. Evaluation of Decision Matrix



Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "How's") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Material Quality	Bluetooth Control	DC Motors	Polywheels in Front with Real Wheel Drive	LitoKala LiPo 12V 2.6A Battery	5V Rechargeable Battery	GPS	Speed	Compass Module	Rounded Edges	Protective Case for Electronics and Wires	Large Rubber Wheels	Support Frame	Arduino Uno/Mega	Electronics and Wiring Insulation
11.4	5.0	Follows User and Avoids Obstacles	▲	▲	○	○	○	○	⊙	⊙	⊙	▲	▲	○	▲	○	▲
9.1	4.0	Battery Life and Charge Time	▲	▲	○	▲	⊙	⊙	▲	▲	▲	▲	▲	▲	▲	○	▲
9.1	4.0	Quiet	▲	▲	⊙	○	▲	▲	▲	⊙	▲	▲	▲	○	▲	⊙	○
11.4	5.0	Safe	⊙	⊙	▲	○	○	○	○	⊙	⊙	⊙	⊙	○	○	▲	⊙
11.4	5.0	Durable	⊙	▲	○	○	▲	▲	▲	○	▲	○	⊙	○	○	▲	○
6.8	3.0	Waterproof	⊙	▲	▲	▲	▲	▲	▲	▲	▲	▲	⊙	○	▲	▲	⊙
11.4	5.0	Portable	⊙	▲	▲	⊙	▲	▲	▲	▲	▲	▲	▲	⊙	○	▲	▲
9.1	4.0	Able to Carry 75 Pounds	⊙	▲	○	⊙	○	○	▲	⊙	▲	▲	▲	▲	⊙	▲	▲
9.1	4.0	Able to Climb Stairs and Curbs	○	▲	○	⊙	○	○	▲	⊙	▲	▲	▲	⊙	○	▲	▲
11.4	5.0	Affordable	⊙	○	○	⊙	○	○	○	▲	○	○	○	○	○	○	○

Legend		
⊙	Strong Relationship	9
○	Moderate Relationship	3
▲	Weak Relationship	1

Figure 7. QFD Chart

Students believe QFD is difficult to learn and difficult to use. Students usually avoid creating a complete QFD chart, also called "house of quality", unless they are required to. This is because QFD chart is complicated and requires a lot of effort. Even the simplified ones as shown in Figure 7 requires the students having strong faith toward this design method, which most students lack at the early stages of product development. Besides, the task of specifying target values seems not so important in the exploratory projects like ours. Since there is no other method that can bridge the gaps between customer requirements and engineering specifications like QFD, we provided opportunities of training and practice, and students started to use it more effectively. We also found that the later we start using QFD in the product development process, the better it works. Therefore, in our project, we completed QFD after finishing the preliminary CAD of the product so that students had some specified model to work on, which usually gave them more faith toward QFD. The survey results of QFD is shown in Figure 8, which is significantly lower than other methods.

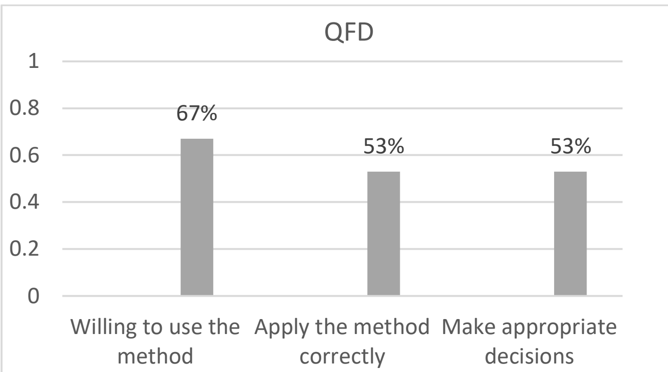


Figure 8. Evaluation of QFD

The preliminary design of CarryBuddy is shown in Figure 9, in which the two front wheels are not only driving wheels but are also capable of climbing over obstacles such as street curb. The design was later modified to the final design, as shown in Figure 10, in order to make the design more compact. The three-wheel design requires the axial height of each wheel to be taller than the 6-inch street curb, which results in an oversized product. By adopting the "penta-wheel" design in Figure 10, we can greatly reduce the size of CarryBuddy.

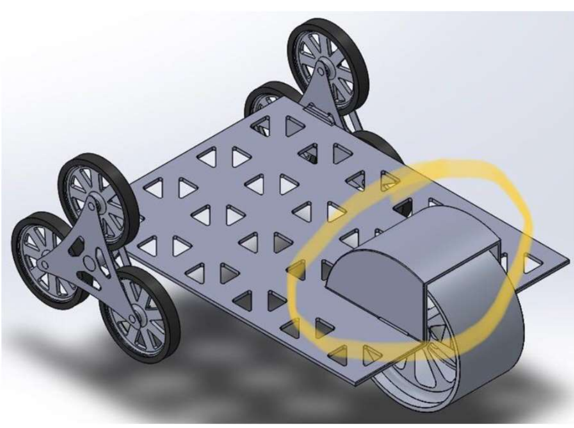


Figure 9. Preliminary Design of CarryBuddy

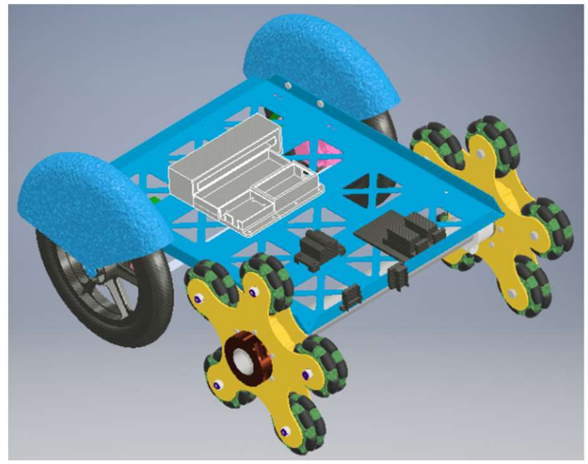


Figure 10. Final Design of CarryBuddy

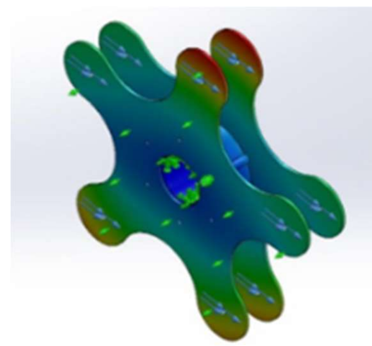


Figure 11. FEA Analysis of the Front Wheel Assembly

2.3 Phase 3: Detail Design

Detail design is completed without using systematic design methodology. It is important to allocate enough time in this phase for students to develop from a rough sketch of a concept to detailed CAD model that is as faithful to the final product as possible. Students sometimes oversimplify the CAD model. A typical mistake students tend to make is forgetting the hardware such as bolts and nuts when connecting parts and later find out that the bolt heads interfere with other parts. Besides, simulations and analyses such as FEA are necessary, which will give students an opportunity to estimate the performances of the final design as well as optimize it. The FEA results of the front wheel assembly is shown in Figure 11, which shows that the front wheel assembly should have enough strength to handle the impact of driving over a street curb.

At the detail design phase, it is necessary to remind students to start considering the manufacturing process as early as possible, as manufacturing methods will change the part design. 3D printing is a powerful technology and is capable of greatly simplifying product prototyping and reducing the product lead time. However, we have noticed that students tend to overly rely on 3D printing without considering alternative manufacturing methods which could be cheaper and work better in the final product.

Prototyping is also necessary at this stage. It does not need to be an exact replica of the final product. Students are encouraged to conduct quick tests on the prototype and find out design flaws that would otherwise be impossible to identify without using a physical model. Building prototypes can also help students better understand the design problem.

3. PHASE 4: PROTOTYPING AND FINAL DESIGN

A functional CarryBuddy prototype is show in Figure 12. After testing, students were able to improve the safety of the design using Failure Mode and Effect Analysis (FMEA). FMEA is a bottom-up analysis method that focuses on each part and determines every way in which the part may fail. For each possible failure, students analyzed its characteristics including how severe it will be, how frequently it will happen, and how easy it is to identify the failure. Then, the risk priority number (RPN) of each failure was calculated by multiplying these three ratings. The failure with the largest RPN was fixed with the highest priority. In this project, students identified the danger of CarryBuddy bumping into its user's leg as the most significant and added several touch sensors at the front and back bumpers to prevent this from happening.

FMEA, as a design method, is easy to understand and easy to use. At the end phase of a product development process, we found that the key to success is encouraging students to analyze the possible chain reactions of the failures. It is also important to encourage students to change the design to avoid possible failure, instead of "making up for it" such as reinforcement, shields, or putting up warning signs. The survey result of FMEA is shown in Figure 13. Students are willing to use this method, which is easy to grasp and support reasonable decision making.

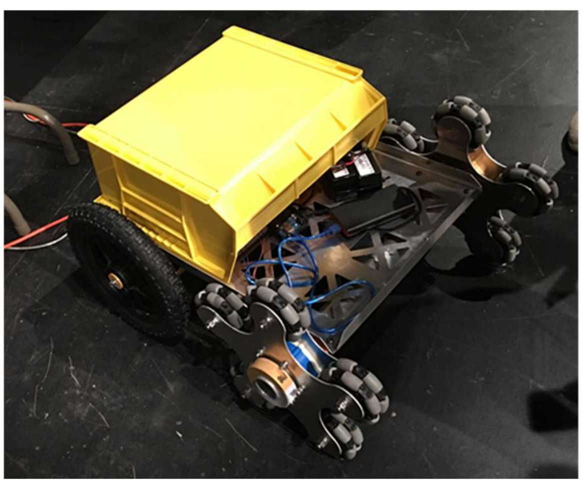


Figure 12. CarryBuddy Prototype

4. CLOSURE

In this paper we discussed a typical product development process in a senior design project, including each design phase, activities, and the design methods used in the process. Such a product development process is typically used in industry. We have paid special attention to how students understand and learn how to use these methods, as well as whether these methods are effective at helping students make decisions. In the future, we are planning to modify the process by increasing parallel activities. We are also planning to use product lifecycle management software to help coordinate and manage the product development process.

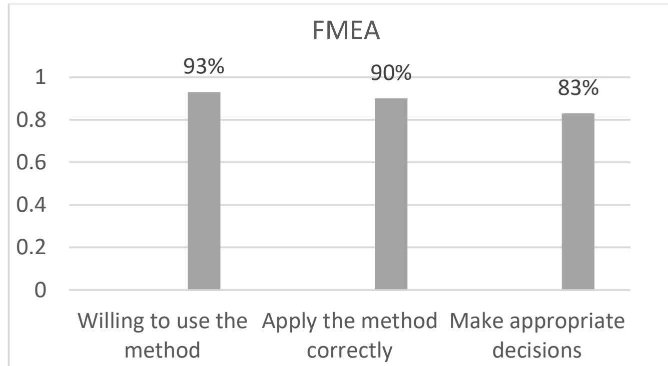


Figure 13. Evaluation of FMEA

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