Proceedings of ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2009
August 30-September 2, 2009, San Deigo, USA

DETC2009-87418

DEVELOPMENT OF AN UMBRELLA CHECKOUT SYSTEM: A CASE STUDY OF A SENIOR CAPSTONE DESIGN PROJECT

Mark D. Fuge*
Department of Mechanical Engineering
Undergraduate Student
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213
Email: mfuge@andrew.cmu.edu

Ben D. Berkowitz
Department of Mechanical Engineering
Undergraduate Student
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213
Email: bberkowi@andrew.cmu.edu

ABSTRACT

Senior capstone design classes allow for both a theoretical and physical basis for learning the principles of the product realization process. By providing an example of the design process for a senior capstone project studied at Carnegie Mellon University, this work highlights insights gained about both the mechanical design process and the product itself. The product studied in this work is an umbrella check system that utilizes Radio Frequency Identification to create a tracking system for a communal resource. The product itself represents a departure from umbrellas as a personal item into use as common good within a community, which has important economic and environmental effects. This work will highlight the various product realization processes that took place in order to translate the product from a user need to a final design, including a traffic analysis based on Markov Models and the construction of several prototypes.

INTRODUCTION

Across a variety of institutions, the senior design capstone project represents the pinnacle of undergraduate engineering design education. By allowing hands-on experience in the product realization process, engineering educators are able to give meaning and real-world value to the theory and methodology of engineering design practices. This paper will guide the reader through an example of this experience by presenting insights gained through the creation of an "umbrella checkout system". This system, developed as part of a senior mechanical design capstone project at Carnegie Mellon University, will highlight insights gained not only about the end product, but about the mechanical design process itself.

The objective of the senior design capstone project was to design a new product or redesign an existing product, based on market needs. The target product selected for redesign was the umbrella. This product was selected due to the ubiquitous adoption of umbrellas as rain protection devices, as well as the fact that the design and use of the umbrella has remained relatively unchanged for a number of years. These reasons created the potential for a new product innovation in the design and use of umbrellas, and acted as a starting point for redesigning the user experience.

The remainder of this paper will demonstrate how skills in the product realization process were developed through the design of a modular "umbrella checkout system". First, focus will be placed on the process of establishing a market need, and how that need is translated into product requirements and specifications [1]. Following that, an overview of the conceptual design process will be presented, including both concept generation and selection [2]. An example of a decision analysis tool will be presented in order to demonstrate how to solve a complex design problem using engineering methods [3]. The development of the embodiment design will be discussed, as well as the use of prototypes to validate engineering concepts. The decisions derived

*Address all correspondence to this author.

from these prototypes will be used to justify changes in the final design, and a business model will be proposed to take advantage of the device as a product of service [4]. Lastly, we will present conclusions from this work which will highlight insights gained about both the mechanical design process and the product itself.

MARKET RESEARCH

The first step in the development of this market driven product was to study the existing product market to determine where a product opportunity existed. This analysis was performed through product dissections and studying user interactions. Through this analysis core customer needs were determined which will be described in this section.

Product Dissection

In order to decide what market opportunities exist with respect to umbrellas a broad survey of the umbrella market was taken. From this survey 4 main types of umbrellas were selected to dissect in order to learn more about their function, manufacturing and assembly processes: a standard wooden handled umbrella, a large golf umbrella, a purse umbrella and an auto open-close umbrella. These umbrellas were carefully disassembled and photo documented and each part was weighed, measured and analyzed for material and manufacturing process [1]. After dissecting these products two main conclusions were developed: umbrellas are already highly optimized for Design for Manufacturing (DFM) and Design for Assembly (DFA).

Umbrellas are designed to take advantage of their high production volume through the use of stamped parts and fasteners. Additionally many parts are reused through the umbrella to reduce the overall part count. These aspects of umbrella design reduce manufacturing processes and assembly steps; therefore an improvement in the manufacturing or assembly sector is unlikely for this product. Product dissection did however reveal significant room for improvement in Design for the Environment (DFE).

User Surveys

After developing a feel for what products exist in the market and how they function user studies were performed to learn how people use their umbrellas and how they interact with the type of umbrellas used in our product dissection. These user studies were performed through the use of a verbal survey incorporating questions such as "What do you do when it rains?" and observing survey participants using their umbrellas and the umbrellas which were provided for them to test. For this survey willing participants were selected from the street such as at bus stops and outside of buildings. This survey provided valuable insight into the priorities of umbrella users which allowed the development of four major customer needs:

1. Umbrellas should be hard to lose
2. Umbrellas should be easy to open and close
3. Umbrellas need to be portable
4. Umbrellas should provide adequate coverage

CONCEPT DESIGN

Following market research, the process of conceptual design began. This involved generating over 150 ideas for product innovations, narrowing those 150 down to 4 main concepts, and then evaluating those concepts using a Pugh chart. This section provides an overview of the methods used in the design process, as well as presenting four main product concepts in detail.

Concept Generation

In order to generate an initial set of concept ideas, we conducted brainstorming sessions based off of findings from market research. Using the identified user needs as a trigger, free association was used to verbally generate ideas, and one team member acted as a scribe to make sure all ideas were recorded. This session continued for 20 minutes, after which a second session began that also used free association, except this time using random words, generated online, to act as triggers. This session lasted for another 20 minutes. At the end of both sessions over 200 ideas for potential product improvements were developed.

One of the strengths of this concept generation process was the ability to harness multiple methods and technologies to supplement the design process. Throughout concept generation, all of the ideas were projected onto a board, so that everyone could freely access prior ideas for inspiration. These sessions were held in a comfortable environment which allowed access to a projector and white board. This allowed the recorded ideas to be easily displayed for everyone to see, but also allowed for embellishment on ideas simultaneously by drawing on the white board. This mixture of methods and technologies provided a great boost in efficiency during the idea generation process. The setup eventually became the basis for most future brainstorming sessions, and was akin to a "war room" often found in industry [5].

Concept Selection

In order to refine and organize the 200 ideas down to 4 main concepts a modified affinity diagram approach was used. This was accomplished by scanning the list and throwing out items that were clearly not viable, resulting in about 150 concepts. After that, electronic tools, such as Excel, were used to display all of the ideas for review. Category headings were then created based on the user needs identified in our market research and then the concepts were organized into categories based on which needs they met. In this way 5 groups were created, each containing an average of 30 ideas. The top 4 ideas in each group were then determined based on preference and experience and placed into

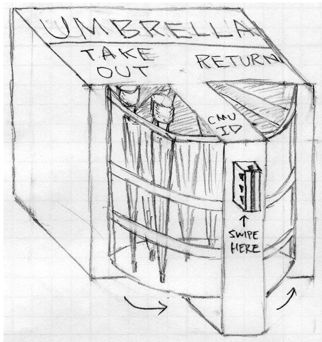


Figure 1: Initial concept sketch for the umbrella checkout system

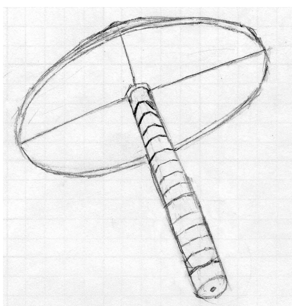


Figure 2: Initial concept sketch for the collapsible ring umbrella

a separate list. After further review, one idea from each of the 4 user needs was selected to become one of the 4 main product concepts.

By using the affinity diagram approach to organize concepts into 5 distinct groupings, the task of assessing 150 ideas simultaneously was simplified, allowing only 30 ideas at a time to be focused on. Additionally, by grouping ideas based on identified user needs ensured that the product concepts would remain viable in the market. If the ideas had been grouped differently, the focus on the needs of end-users might have been lost.

The concept selection stage resulted in four product concepts: an umbrella checkout system for campuses, a collapsible ring umbrella, a Velcro mounted umbrella, and an umbrella whose canopy shape and size could be adjusted. The umbrella checkout system, seen in Fig. 1, allows users to “check-out” an umbrella for temporary use, and deposit it into a different unit once they reach their destination. The collapsible ring umbrella, seen in Fig. 2, is designed to improve portability by collapsing in on itself, the same way that flexible Frisbees work. The Velcro mounted umbrella, seen in Fig. 3, has a strap that is Velcro on one side that can attach to mating piece on a backpack or jacket. The adjustable canopy umbrella, seen in Fig. 4, has multiple stops on the shaft so that a user can choose to only partially open the umbrella when traversing through a crowd.

To decide on a final concept, a Pugh chart was used [6],

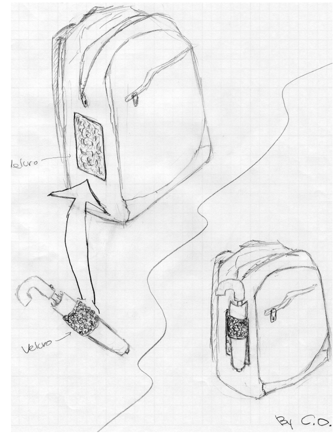


Figure 3: Initial concept sketch for the velcro umbrella

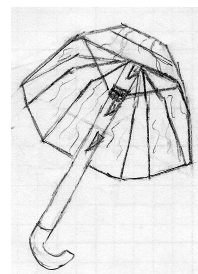


Figure 4: Initial concept sketch for the adjustable canopy umbrella

which contrasted the 4 concepts against the standard umbrella. The criteria and weightings were selected based on market research and experiences from product dissections. The Pugh chart used to evaluate the concepts can be seen in Fig. 5. The results of our Pugh chart indicate that the best choice for a new product concept is the Velcro umbrella. Unfortunately, the Velcro umbrella, while best fitting market needs, was not sufficiently complex for a mechanical design course. Due to this, the umbrella checkout system was chosen, which scored highly on the Pugh chart and had sufficient mechanical complexity for the senior design course.

DECISION ANALYSIS

The most important aspects of designing and implementing the umbrella checkout system are determining where to place the checkout units and determining how many units to place at each location. In order to determine these characteristics, traffic flows on an example campus (Carnegie Mellon University) were studied, and the results were used to aid in making better design decisions. This was achieved using two methods: a simulation of traffic flow, and counting the number of people going into and

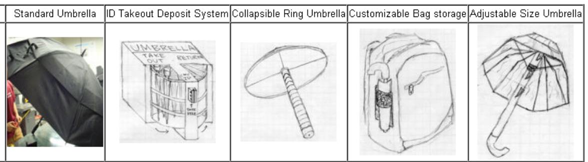
Description		Standard Umbrella	ID Takeout Deposit System	Collapsible Ring Umbrella	Customizable Bag storage	Adjustable Size Umbrella
Sketch						
Criteria	Weight	Datum	Design 1	Design 2	Design 3	Design 4
Durablity	1	0	0	0	0	0
Asthetics	1	0	0	0	0	-
Weight	2	0	0	-	0	0
Portability	3	0	++	+	+	0
Coverage	2	0	0	0	0	+
Ease Of Use	3	0	-	0	+	0
+		0	6	3	6	2
0		0	6	7	6	9
-		0	3	2	0	1
Net Score		0	3	1	6	1

Figure 5: A Pugh chart was used to evaluate our product concepts

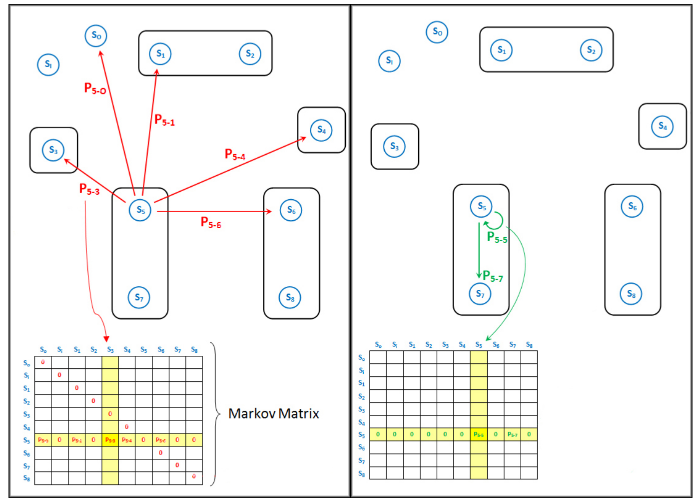
out of each major doorway on campus. The results of the decision analysis eventually resulted in choosing a smaller, modular design for the units that improved placement flexibility.

Markov Simulations

In order to predict traffic flow on campus, a Markov model was used to simulate individual people moving about campus. A Markov matrix expresses the probability that something in a given state at some time will move to another given state at the next time [7]. In the model, it expresses the probability that somebody leaving a certain doorway will move to another given doorway. Two matrices are needed for the model because the probabilities of where users are going to move are different for users entering and leaving a given doorway. For example, a user exiting the upper door of an academic building might go to the library, the student center, or some other building. A user entering the same door must exit through the same door or any other doors along the length of the building. Using these movement probabilities, a model of campus was constructed and a rainy day was simulated to see how traffic moved around campus. Figures 6a and 6b describe the process in greater detail. The results of the simulation are depicted in Fig. 7.

Traffic Counting

In order to provide an order of magnitude estimate of the amount of traffic seen on CMU's campus, the team decided to physically count traffic flow at the major doorways on campus. To do this, a java applet that could run on different computers and would allow us to manually record when people entered or exited a building was created. The team collected the time-stamped data and determined that the maximum differential between people entering (dropping off an umbrella) and leaving (taking an umbrella) was 171 people. This indicates that in order for the system to be fully stocked, the capacity of the system would need to be greater than 170 umbrellas, assuming everyone took and returned umbrellas equally.



(a) Outside Travel (b) Inside Travel

Figure 6: Markov matrices used for evaluating travel patterns

Conclusions

The results from both the Markov model and the empirical counting study directed the choice to make a smaller modular checkout system. The main limitation in the traffic flow simulation is that the Markov matrix probabilities are difficult to accurately determine, since they are highly dependent on the environment and cannot be measured feasibly. In addition, the manual counting of traffic on CMU's campus is highly time-dependent, and thus does not provide a statistically accurate measure of CMU's traffic patterns. Due to this, the results are more helpful when considered in a qualitative sense.

The results indicate that there exist nodes or locations for which the net flux of umbrellas is not zero. From a design perspective this means that certain units will have an excess of umbrellas over time, and other units will have very few umbrellas. With this in mind, the team decided to reduce the size of each unit in order to make it more modular. By decreasing the size of the unit, areas of campus can be populated with the amount best matched to the capacity needs of that area. The smaller size also means that the unit can be transported using a standard hand cart, in the event that units need to be moved across campus.

EMBODIMENT DESIGN

Features

In order to determine the features and criteria necessary to judge and evaluate the design alternatives, a series of product requirements were developed. After discussing potential criteria the team decided on three final requirements: the system must be fast and easy to use, modular and low cost.

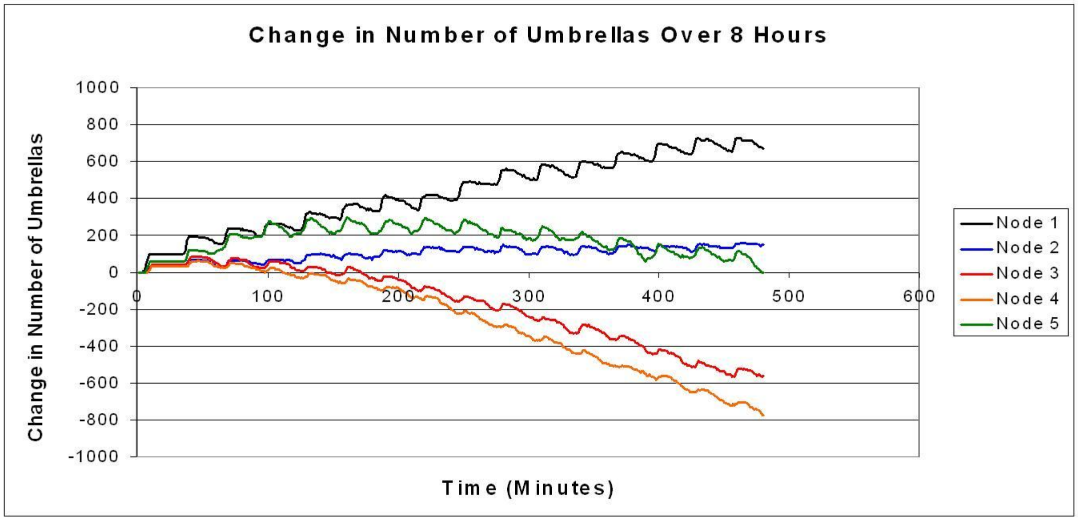


Figure 7: The results of the Markov simulation showed unequal traffic flow

Design Alternatives

Considering these product requirements, the team developed potential concepts for the realization of the design through sketching them on a white board. These ideas were then presented through a gallery style from which a final design was selected. The final design consists of a small modular unit with a simple design and low part count. Umbrellas are fed by gravity through the system due to the sloped design of the device, and then are dispensed via a motorized turnstile at the base. When the umbrellas are no longer needed they are returned to the device through a one way gate. The flat sides of the device allow multiple units to be placed next to each other for an umbrella checkout system with multiple locations to take out and return umbrellas and allow the system to be easily scalable for the traffic volume.

Prototype 1

One important factor of the design criteria was that the system be fast and easy to use. As a result a first prototype was developed in order to test user interaction with the system design and to refine the system geometry through testing. The body of the prototype was built with MDF (Medium Density fiberboard) wood material and painted red. The ramp on the top of the device was lined with low-friction Teflon material to prevent binding. For the input chute, there was a latch attached to a torsional spring to make sure that umbrellas cannot taken out from the receiving end once they are returned. Also, for the output chute, a manual turnstile was developed to make sure that one umbrella is taken out at a time. Views of the first prototype can be seen in Fig. 8

Figure 8: The first prototype focused on the design of user interaction

Prototype 2

The second prototype was a modified version of the first prototype in order to test the integration of an electrical system into the device. The electronic system is activated by users who swipe their ID card which tells the device to dispense an umbrella. The device dispenses umbrellas by rotating a turnstile allowing only one umbrella to be dispensed at a time. The motion of the motor is controlled by a microcontroller which rotates the turnstile by approximately 90 degrees to dispense a single umbrella. In addition to the electric system, ventilation holes were placed on the sides of the device to facilitate drying of wet umbrellas through free convection. The input chute of the device was machined down to have a ramp in order to make it easier for users to return their umbrellas back to the system after use. A removable drip tray was added on the bottom of the device to collect the water runoff from wet umbrellas while they are stored inside the device. For the second prototype, the actual umbrellas, specially chosen for the prototype, were used to test the function of the device

Final Prototype

For the final prototype, a new device was designed and constructed. A new body of the device was built using MDF wood in order to accommodate a smaller footprint. The shell was also designed to have an access panel on the side to provide easier access to the inside of the device for the purpose of design for maintainability. The major difference between the second and final prototypes was a more sophisticated electrical system implemented on the device to achieve the features of a fully automated umbrella dispensing system and to incorporate a Radio-frequency identification (RFID) tag reader to track the actual flow of umbrella usage. During the planning and development of the prototype, a barcode scanner and RFID reader were tested and evaluated based on cost and reliability. Ultimately the RFID scanner was chosen due to its independence of the umbrella orientation and dynamics.

The dispensing system incorporates a gearbox with a worm drive to power the turnstile and prevent being back driven by users trying to forcefully remove umbrellas. As users swipe their ID cards, the system is activated and the motor turns 90 degrees to dispense an umbrella, during which that umbrella is associated with the user to prevent theft.

The users can later return their umbrellas by putting them into the input chute of the device, which activates an RFID reader to read the RFID tags on the umbrella being returned. The RFID reader does not turn on unless an umbrella actually passes the single way latch, which prevents the potential of scanning an umbrella without returning it and allows the system to save power. Additionally an LED was incorporated into the unit to let users know when their umbrella has been received The returned umbrellas are recognized by the system as having been returned and ready to be taken out by other users.

A picture of the final prototype can be seen in Fig. 9.

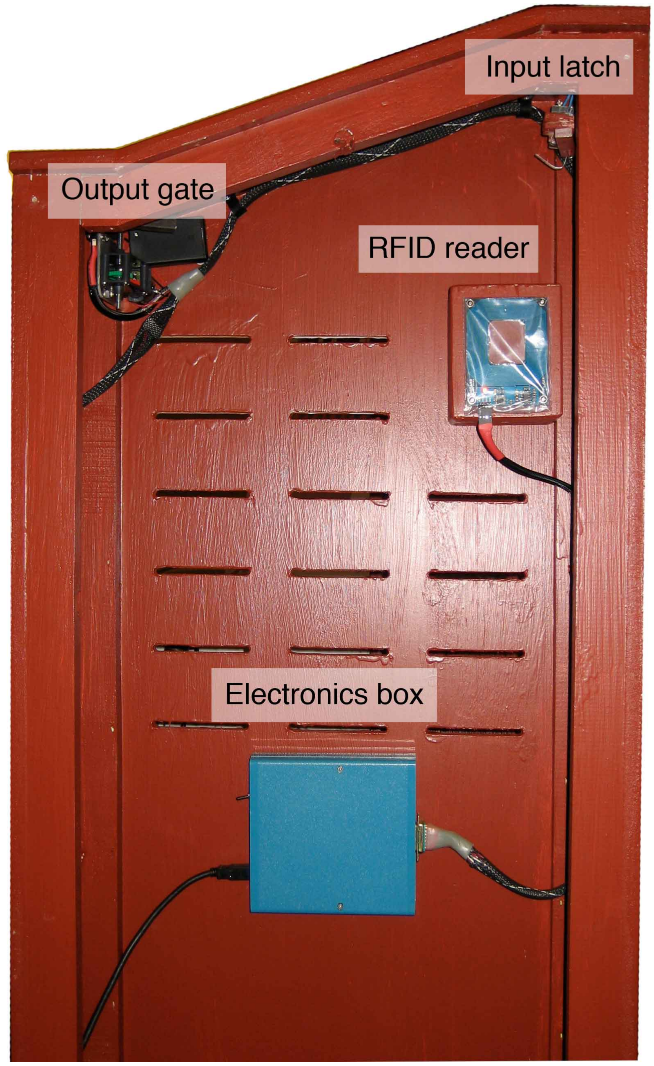


Figure 9: The interior components of the final prototype

DESIGN EXPOSITION AND USER TESTING

The final prototype was presented and tested at the course Design Exposition, where some final user testing was conducted and valuable feedback about the design was collected from third party participants. The design exposition was an all-day event where local residents, students, faculty, and media came by to critique the capstone project [8–10]. For the exposition, the fully functional prototype interfaced with a computer to display feedback to the user as they interacted with the device. The system monitored the RFID signals of the umbrellas that were checked into the system, and used a simple First-In/First-Out list to display the current contents of the unit.

The conclusions drawn from the expo indicated the need for a more powerful RFID reader and that demand for the product was high. During user operation the distance of the umbrella to the reader was particularly important, as the RFID reader was only strong enough to detect the tag when the umbrella was placed against the reader. This caused confusion among users when the umbrella was not recognized instantly, and could be alleviated by using a more powerful RFID reader that would not be as susceptible to umbrella distance. Despite this issue, users were very excited about the system as a whole. Several people asked "When is this going to be on campus?" or "You should talk to CMU about this". Some users had previous issues with communal umbrellas being stolen, and many thought the system would be more accountable.

FINAL DESIGN

In order to compare the system to current market alternatives, a QFD analysis was performed to better delineate how the product might gain market advantage over competitors in satisfying customer and institution needs [6]. Since the umbrella checkout system has no direct competitor, the design was benchmarked against the possible alternatives that customers may choose in place of using the system. This included bringing your own umbrella from home, not using an umbrella at all, and placing buckets of free umbrellas for people to take.

After conducting QFD, it was concluded that the system, while not excelling at satisfying the needs of either institutions or users, provides a good compromise between the needs of both groups. For institutions, the preferred option is for people to either bring their own umbrellas or use no umbrellas at all, since it represents the least amount of cost and effort on the part of the institution. Users, on the other hand, would rather have a free system of umbrellas that they can just take and use freely. Unfortunately, the solution that is optimal for one group is directly opposed to the solution for the other group. The umbrella checkout system creates a workable compromise that comfortably, though sub-optimally, meets the needs of both groups.

The final production design is comprised of four main systems: the shell, the electronic subsystems, the output turnstile and the input gate. The shell is what encompasses all of the internals. It is manufactured out of 18 gage low carbon steel for durability. It can be manufactured through standard sheet metal processes using a sheet metal bending brake, shear and spot welder. These simple processes are the most cost effective at the predicted annual production volume of 2000 units per year and are also easily scalable for increased production volumes. One side of the shell is removable to allow easy access to the electronic components for upgrading and maintenance. Additionally the shell also provides physical support for everything else to create a long lasting durable unit.

The electronics subsystem is the heart of the unit. It consists of a microcontroller, a card scanner, and an RFID reader. The microcontroller provides the logic to control the other systems. The card scanner allows the system to identify users, and the RFID reader allows the system to identify umbrellas. These units are enclosed in a waterproof injection molded housing to ensure a long life despite the moisture generated by the wet umbrellas.

The output turnstile is what dispenses umbrellas to the user.

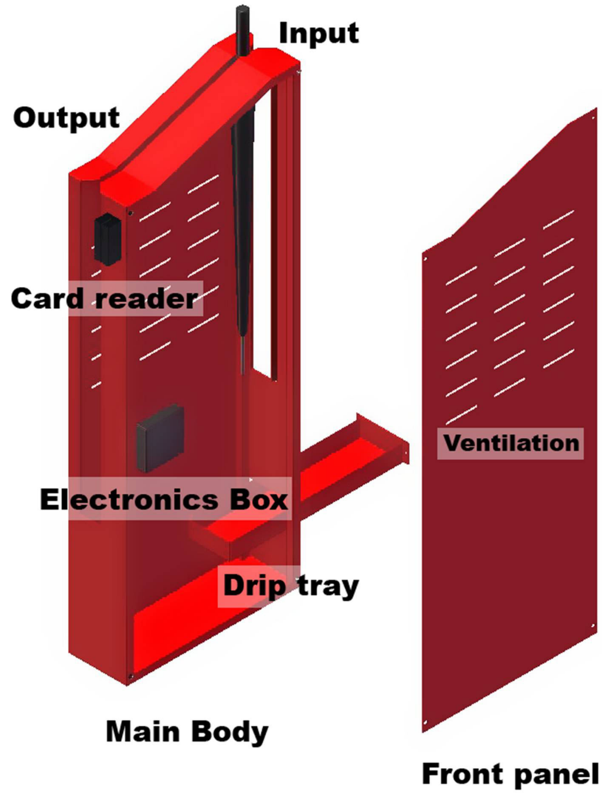


Figure 10: An exploded view of the final design

It is a small motor attached to a worm drive gearbox. On the output shaft of the worm drive are four turnstile arms. An infrared break-beam sensor provides feedback about the turnstile's position. This system ensures that an umbrella is dispensed when a user swipes their ID card and that umbrellas cannot be stolen by force from the system

The input gate is a one-way gate, allowing umbrellas to be returned to the system. A limit switch provides a signal when the gate is open to turn on the RFID reader thereby saving power and making the unit more energy efficient.

Examples of each part of the system can be seen in Fig. 10. When fully assembled and placed next to adjacent units the unit appears as in Fig. 11

BUSINESS MODEL

In addition to dispensing umbrellas, the umbrella checkout system acts as a vessel by which umbrellas can be transformed from a product of consumption into a product of service. Prior to the development of this product, umbrellas had to be purchased by individual users, and the maintenance and eventual disposal of the umbrella lay in the hands of the individual. With the proposed model, umbrella ownership becomes centralized to an or-

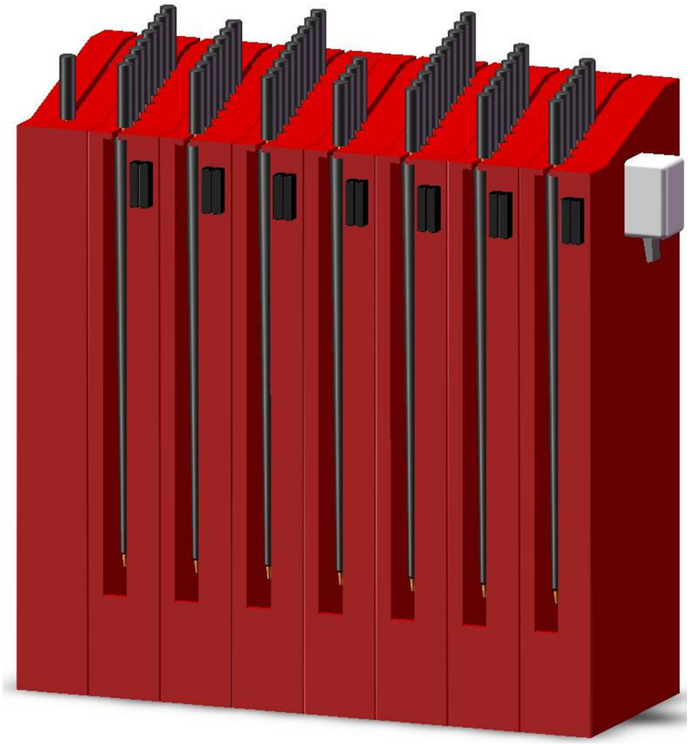


Figure 11: The final design is modular such that it can be grouped with other units

ganization or community. This has important business and environmental factors that make it more appealing than having users purchase their own umbrellas.

From the standpoint of a business venture, the benefits of the product arise in the potential for it to be used as a rental product, rather than through direct sale. Companies or campuses could hire a company to lease them a set number of umbrella dispensers and umbrellas, and to maintain the necessary quantity over the lease period. Campuses benefit from this approach since it allows them to have an outside company handle all of the logistics regarding the placement or upkeep of the units. The leasing company benefits since it maintains control of the units, and can reuse parts from broken or old units at the end of the lease, especially for electronic components, reducing their manufacturing cost.

More influential than the business utility of a rental system is the ability to control the recycling and end of life of the product for environmental purposes. Current models of umbrella use make it difficult for individuals to return the umbrella to the manufacturer upon its end of life. Umbrellas are inexpensive enough that users would rather throw the umbrella into the trash and buy a new one than properly recycle old umbrellas. With the proposed product, the user can place broken or old umbrellas into the unit to be picked up and recycled by the leasing company. This allows the company to properly reuse or recycle components at a minimal cost to both the user and the company. In addition to the financial incentives, this creates a positive impact on the community and provides the additional feature of proper disposal for the users. This product is one embodiment of new "Cradle to Cradle" thinking, where products of consumption are recast as products of service [11].

The financial viability of this system depends on how the leasing company charges the end user. Revenue for this system is derived from several sources:

1. If users lose the umbrella, they pay a nominal fee approximately 5 times the original cost of the umbrella.
2. A yearly fee can be charged for the use of the system in places such as corporate or college campuses.
3. A per-use fee could be applied the use of the system for places such as airport or other public spaces.

A combination of any of the above methods can be used to generate revenue from the distribution of the product.

For an example of how this product might be implemented, consider a model college campus of approximately 5,000 users. In order to outfit a campus of this size approximately 2,000 umbrellas would be appropriate. This translates into 160 dispenser units. At a manufacturing cost of $300 per unit, this initial investment would total $50,000 for the entire campus. For each lost umbrella, it is assumed that it will cost between $2-$5 to replace and restock the system. If the worst case of $5 is chosen, and it is assumed that 80 umbrellas are lost per month, the total upkeep cost of the system would be $400 per month.

If the leasing company chooses to offset the initial cost of the system as well as the upkeep cost entirely from unreturned umbrellas, they would need to charge each user $20 for a lost umbrella. If the leasing company chooses to offset the cost of the system using only an annual fee, then each of the 5,000 users would have to pay $3.87 per year. In practice, a combination of these two methods would be used to pay for the cost of the system. For example, if each user pays $10 per lost umbrella, then the entire user population would pay an annual fee of approximately $2.00 per user. These estimations outline the break-even point for the system. By charging more than this amount for either lost umbrellas or as an annual fee, it becomes profitable to produce this system. These values were calculated assuming a discount rate (r) of 13% over a payback period (N) of 5 years using the Net Present Value formula in Eqn. (1), where P is the initial $50,000 investment in the system. Feedback during the design exposition indicated that users would be more than willing to pay the proposed amounts for this service.

$$R = P\frac{r(1+r)^N}{(1+r)^N-1} \tag{1}$$

CONCLUSION

As a result of the senior capstone design course it was possible to develop an “umbrella checkout system” which satisfied the four identified customer needs: Umbrellas should be hard to lose, easy to open and close, portable and provide adequate coverage. The system addresses these needs by removing personal umbrellas and instituting the concept of communal umbrellas regulated through RFID technology. Through this system users can swipe an identification card to remove an umbrella, use the umbrella while they travel outside and return the umbrella when they arrive at their destination. Through this system umbrella users will not have to worry about loosing their umbrellas or forgetting their umbrella when it rains. Additionally because users no longer have to carry umbrellas when they are not in use portability is no longer a concern. As a result, large durable umbrellas which provide sufficient coverage and are easy to open and close can be used in the system.

In addition to providing the user benefits mentioned, the system also reduces the environmental footprint of umbrellas by centralizing umbrella ownership and control. Through this centralized ownership, broken umbrellas can now be recycled into new umbrellas instead of ending up in landfills and overall umbrella waste is reduced by preventing personal umbrella loss.

During the design process the team used a highly collaborative approach to ensure that all team members were up to date on all facets of the project. In order to do this the team used a comfortable space on campus equipped with a white board and a projector for the majority of the team meetings. As a result the team was able to clearly demonstrate project ideas and the status of the project in addition to brainstorm solutions to problems quickly and effectively. The team also used an online file sharing program to allow collaborative file editing and to provide a central database for all of the project information. This database ensured that everyone had access to up to date files and had easy access to all of the information that they needed. For the public display of information and documentation, a new collaborative form of information creation called a wiki was utilized to publish the work [1–4, 12]. The use of the wiki, along with other online collaboration tools allowed the team to increase productivity in all phases of the design process, whether the team was collocated or not. The key insight from the entire process is that while collaborative spaces and interpersonal communication are still important elements in the design process, it is getting easier and cheaper to create online design environments where product realization can take place. As engineering design moves toward a global community, this technology will be a key enabler in the product realization process as seen, even if on small scale, within this capstone project.

ACKNOWLEDGEMENTS

The authors would like to thank the other half of our design team, Michael Cushman and Changho Oh, for their dedication to the capstone project. Without their expertise, motivation, and insights a project of this magnitude would simply not be possible. We would also like to thank Professor Jeremy J. Michalek and Norman Shiau of Carnegie Mellon University for their invaluable advice throughout the development of our capstone project, as well as with the review of this paper. Without them, this paper would never have seen the light of day. We also gratefully acknowledge the funding given to us by the Mechanical Engineering department for the development and production of our prototypes.

REFERENCES

[1] Fuge, M., Berkowitz, B., Cushman, M., and Oh, C., 2008. Umbrella - ddwiki. [Online: ‘http://ddl.me.cmu.edu/ddwiki/index.php/Umbrella’ accessed 15-October-2008].

[2] Fuge, M., Berkowitz, B., Cushman, M., and Oh, C., 2008. Umbrella redesign - ddwiki. [Online: ‘http://ddl.me.cmu.edu/ddwiki/index.php/Umbrella_redesign’ accessed 15-October-2008].

[3] Fuge, M., Berkowitz, B., Cushman, M., and Oh, C., 2008. Umbrella traffic flow analysis - ddwiki. [Online: ‘http://ddl.me.cmu.edu/ddwiki/index.php/Umbrella_Traffic_Flow_A accessed 15-November-2008].

[4] Fuge, M., Berkowitz, B., Cushman, M., and Oh, C., 2008. Umbrella check-out system - ddwiki. [Online: ‘http://ddl.me.cmu.edu/ddwiki/index.php/Umbrella_final_report’ accessed 18-December-2008].

[5] Liker, J. K., 2003. *The Toyota Way*. McGraw-Hill.

[6] Dieter, G. E., and Schmidt, L. C., 2009. *Engineering Design*. McGraw-Hill Higher Education, Boston.

[7] Meyn, S. P., and Tweedie, R. L., 1996. *Markov Chains and Stochastic Stability*, 1 ed. Springer.

[8] WPXI, 2008. “Cmu students host innovative product expo”. *WPXI-Pittsburgh News*, December 8. http://www.wpxi.com/news/18227479/detail.html.

[9] Zlatos, B., 2008. “Cmu engineers innovation at student exposition”. *Pittsburgh Tribune-Review*, December 8. http://www.wpxi.com/news/18227479/detail.html.

[10] Highfield, D., 2008. “Cmu students show off inventions”. *KDKA-Pittsburgh News*, December 8. http://kdka.com/video/?id=49955@kdka.dayport.com.

[11] McDonough, W., and Braungart, M., 2002. *Cradle to Cradle: Remaking the Way we Make Things*. North Point Press.

[12] McGaughey, A., and Michalek, J. J., 2008. “Wiki-based learning in the mechanical engineering classroom”. In American Society for Engineering Education Annual Conference.