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Teaching Market-Driven Engineering Design with an Agent-Based Simulation Tool

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ABSTRACT

In product design, there is often a disconnect between the engineers creating the product and the marketing team determining the best characteristics for the product. The research areas of "design for market systems" and "decision-based design" seek to bridge that disconnect through quantitative approaches that facilitate simultaneous technical design and marketing decisions. However, these market-driven design frameworks have been primarily evaluated in the context of industry case studies, with limited integration into engineering education. This article presents the development and implementation of a simulation tool for teaching market-driven design in undergraduate engineering design courses. This classroom tool demonstrates the basic relationships between product design decisions, pricing and marketing choices, and predicted market success, by simulating the interactions among producers and consumers in a market system. The product attributes influence the cost and consumer utility of the product, which, along with price, affect market dynamics. The simulator was implemented in a third-year undergraduate design course to introduce the concept of market-driven product design, allowing student design teams to assess the impacts of different design variables on the market success of their design projects. Surveys and written reflections by the students were used to evaluate the simulator's value in contributing to self-reported learning. The results showed that a majority of students expressed that the simulator provides a meaningful and engaging way to learn about market-driven design concepts.

INTRODUCTION

Undergraduate engineering courses are increasingly including, if not focusing primarily on, design projects, and engineering students are often required to design, construct, and evaluate a prototype product in a one-semester course. As a result of the demands of such a course, and of engineering curricula in general, engineering students often lose sight of the market needs of their designs, and they rarely are able to optimize their designs with respect to profitability. Instead, students may have a rough concept of product success factors from personal experience, and they make qualitative judgments regarding how the characteristics of a conceptual design will affect its marketability. This qualitative assessment is useful in introducing the concept of market-driven design, but an intuition-based approach varies from student to student and generally falls short of the techniques available within the design research community.

This paper proposes and evaluates an approach to use agent-based modeling through a market-driven design simulation tool for engineering classrooms. A market simulator is developed to meet the needs of engineering students who are evaluating how their design projects would perform in a marketplace with competing products and heterogeneous consumers. The consumers in the target market are modeled as “agents” with unique utility functions, and they each choose the product that maximizes their individual utility, which may or may not be the students’ new product. The students are then able to modify their product’s attributes and their pricing strategies in efforts to improve the product’s market share or profits. This simulation is intended to be used to teach students about the broader design context in which their projects fit, enhancing their systems thinking abilities and their interdisciplinary skills.

An initial version of the market simulation tool was developed based on student needs documented in the literature and observed by the authors, as well as advances in the engineering design and systems modeling research fields, described in the Background section. The requirements, development, and description of the simulation tool itself is presented in the Model Development section. Next, the Course Implementation section describes the course context in which the tool was first used, as well as the first implementation and its results. The final two sections discuss the findings and outcomes, followed by a summary of the conclusions.

The market simulator and accompanying curricular materials are available for download at www.designspacelab.com/classroom-simulator.

BACKGROUND

This work addresses a gap in engineering design education by applying market-driven design concepts and agent-based modeling tools. This section presents some necessary background in each of these three areas that motivates and provides a foundation for the present study.

Engineering Design Education

In the 1950s, the American Society for Engineering Education (ASEE) initiated a major effort to improve engineering education in universities by studying existing programs. This resulted in the

"Grinter Report," which put forward a number of recommendations for improving engineering education, including a baseline of scientific course topics, a selection of courses focused on design and analysis, and the inclusion of economic and social aspects in engineering subjects (Grinter 1994). A later study looked into the implementation of these changes in engineering universities in the United States, finding that engineering education had in fact shifted towards teaching the fundamentals of scientific principles, but there was still insufficient emphasis on design education (Nicolai 1998). That study concluded that the engineering industry was negatively affected by this omission, as newly hired college graduates were underperforming in professional engineering environments.

More recent research efforts have specifically identified deficiencies in design education, in particular in meeting the design-related knowledge, skills, and abilities that graduating engineers need (Nguyen 1998; Crawley et al. 2014; Sanders 2012; Center for Education 2011; Systems Engineering Vision Project Team 2014). The standards set by ABET, the organization that provides accreditation to most engineering education programs, have pushed for the adoption of capstone engineering projects to provide students with experience in solving practical design problems (Dym 1999). Furthermore, some institutions are also providing so-called "cornerstone" engineering projects for first-year students, to expose them to the design process early and inspire motivation for becoming an engineer (Dym et al. 2005). Depending on the level of student expertise and the specific engineering discipline, the subject matter of such design courses can range from a high-level product design scenario, reverse engineering an existing machine, or an in-depth technical analysis of an industry problem.

One contemporary approach for re-designing engineering education with industry needs in mind is the CDIO model, named after the four steps in this process: conceive, design, implement, and operate (Crawley et al. 2014). This model, drawn from a multi-university partnership along with several major companies that employ engineers, focuses on coupling engineering course material more closely with design activities, based on the understanding that students learn better through application. The CDIO approach specifically emphasizes the "external and societal context" as well as the "enterprise and business context" (Crawley et al. 2014), motivating this paper's integration of market-driven design in engineering education. A similar approach is the concept of "integrative STEM education," a model for design-based learning that intentionally integrates the concepts of science, technology, engineering, and mathematics (STEM fields) with one another and with other educational disciplines (Sanders 2012). This approach has led to evidence of the value of teaching through engineering design as a way to improve student interest and learning.

While student learning can be challenging to objectively measure, particularly with small sample sizes and open-ended assignments, perceived student learning is often used in its place (Bacon 2016). Although some literature supports the correlation between self-reported learning and cognitive learning (Chesebro and McCroskey 2000), others argue that these represent two different constructs that are not tightly coupled (Bacon 2016; Sitzmann et al. 2010; Stehle, Spinath, and Kadmon 2012). Self-reported learning has been found to be more closely related to affective outcomes such as student motivation and reactions than actual cognitive learning (Sitzmann et al. 2010). Furthermore, the correlations between these affective outcomes and cognitive learning have been found to be stronger when the course (1) includes external feedback on learner performance, (2) is classroom-based rather than online, and (3) emphasizes interpersonal skills (Sitzmann et al. 2010). While the current study is conducted within a course that meets all three of these criteria, it is important to note that the self-reported learning results are more indicative of student motivation levels and reactions than measured cognitive learning.

Market-Driven Design

A particular area of interest in engineering is consumer product design. Compared to larger industrial systems that are tailored and sold to individual clients, a consumer product is exposed to a wide variety of users and environments that influence the product's success. In product design, the success of a design process depends on areas that do not fall under the traditional umbrella of engineering education, such as economics, psychology, social policies, ethics, and environmental studies (Shiau and Michalek 2009).

Recognizing the importance of these non-engineering factors for product success, many modern engineering design textbooks account for some of these market needs in their design processes and tools, notably Ulrich et al. (2020) and Dieter and Schmidt (2013). These texts, among others that contain elements of design thinking (Brown and Katz 2011), emphasize the identification of the market opportunity, elicitation of consumer needs, and benchmarking of competitive products as essential steps in the beginning of the product development process. They also recognize the importance of finance and marketing in product design, including chapters on the development of marketing and sales plans as well as detailed economic analysis. Pahl et al. (2007), while known as an engineering design reference with a more technical focus, also points out the importance of information flow between engineering departments and marketing, sales, product planning, and production. In addition, quantitative tools, such as the quality function deployment (QFD), have become common in engineering design curricula to guide students through the process of connecting market needs with technical specifications (Dieter and Schmidt 2013). While these texts and tools have added market components to design education, they generally treat market needs as discrete steps in the engineering design process, rather than an integrated consideration that influences all decisions during design.

A relatively new approach to product design in the engineering design research community is market-driven design, which seeks to ensure that engineered products will be both desirable

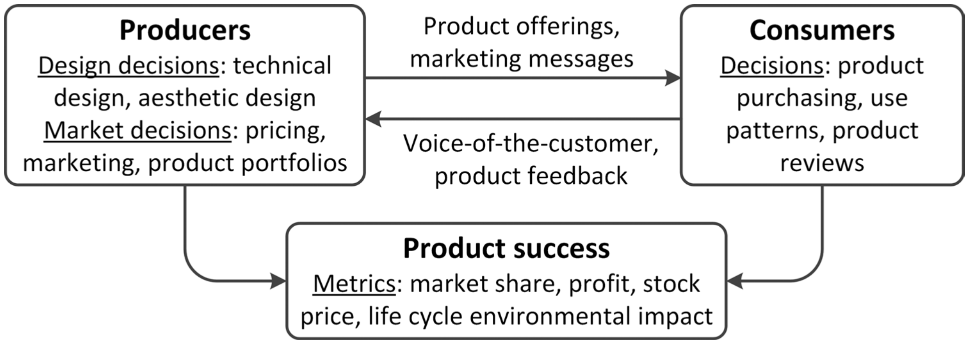

Figure 1. General framework for market-driven design decisions and metrics.

to consumers and profitable to producers. Two specific market-driven design frameworks in the literature are known as "design for market systems" and "decision-based design" (Hazelrigg 1996; Wassenaar and Chen 2003; Lewis, Chen, and Schmidt 2006; Michalek 2008). These approaches model the design process in a way that explicitly and quantitatively accounts for consumers, competing producers, and policy makers. This is accomplished by combining multi-disciplinary models of engineering analysis, consumer behavior, marketing, and economics to support concurrent design, pricing, and strategic business decisions. Figure 1 shows a general framework for market-driven design, illustrating the connections between product success and decisions made by producers, the companies that design and market products, and consumers, the purchasers of these products. A key objective in this type of modeling is to understand how designers make and should make decisions within a market context that includes businesses, consumers, and policy makers acting individually. However, little work has been done to incorporate these concepts into classrooms and teach these approaches to undergraduate engineering students.

Some previous studies have looked into classroom approaches to teaching concepts similar to market-driven design to engineers. For example, approaches for teaching both market strategy in the design process (Bauer 2005) and general product design skills (Condoor and Doty 2008) have been proposed without explicit interactive software components, which have been shown to be effective for improving student engagement and performance (Kadiyala and Crynes 2000; Lloret et al. 2009). Other studies have examined software that is useful for design education, such as problem solving in engineering (Robertson and Radcliffe 2006; Bzymek and Xu 2012), concept generation (Eng, Bracewell, and Clarkson 2009; Bryant et al. 2006), professional design practice (Chesler et al. 2013), and applying disciplinary analyses (Brophy, Magana, and Strachan 2013), but not with respect to market-driven design or similar topics. Similar work has been performed for the design of vehicle interiors, by using a software framework to facilitate the design process (Kumar et al. 2007). However, little has been done to develop and validate market-driven design curricula with interactive tools to reinforce the concepts.

Agent-Based Modeling

To bring these concepts together in an educational setting, this paper describes the development of a software tool to simulate product design in educational settings using agent-based modeling (ABM). ABM was chosen from among the major systems modeling approaches (which also include system dynamics and discrete event simulation) due to its decentralized nature and its ability to generate system-level effects from individual-level behaviors (Borshchev and Filippov 2004; Epstein 2006). With ABM, producers and consumers can be modeled as agents, which interact with one another through a simulated market. ABM has been used successfully in the field of business to simulate market mechanisms (Rand and Rust 2011), and it has also been used in limited research in market-driven design modeling (Wang et al. 2011; Mashhadi et al. 2016; Zadbood and Hoffenson 2017).

The ABM method is useful in analyzing the large-scale behavior of a system caused by interactions among small-scale entities. In many cases, it is simpler to define governing laws for each participant in a system rather than prescribing the behavior of the entire system. By running an ABM simulation, the agents' interactions generate larger-scale behavior in the system (Epstein 2006). This emergent behavior can be compared with mathematical models of the overall system to validate the system or investigate new insights. A benefit of using ABM in an educational context is that agent behaviors are simple to formulate and explain, and the emergent behavior of the system can then be compared to microeconomic principles.

MODEL DEVELOPMENT

To be useful in an educational setting, a modeling tool must satisfy a number of requirements. First, the model should be easy to use, with only minimal effort needed to learn the tool and enter the necessary model information. Second, the model should be transparent in its underlying mechanisms, so that students can see how the model functions and learn from its operation. Third, the model should be able to produce logical results that can be verified with simple reasoning.

The model proposed in this section applies methods from the market-driven design literature to create a simulation of a product market that is approachable from an educational perspective. Student designers, or "producers," will be aiming to create a single product with fixed design characteristics. To determine how consumers will view the product, utility analysis is applied. This method involves determining some measure of utility based on the product's characteristics, such that the characteristics can be entered into a utility function to determine the overall score (Hazelrigg 1996). Depending on the product, creating an accurate utility function can be difficult or impossible, but there are a number of well-established methods to estimate utility.

Since the aim of this model is to teach market-driven design concepts, rather than to present accurate forecasts of market behavior, the Kano model for utility functions is used to characterize how the chosen attributes affect consumers' demand for the product. This model is intuitive to understand and simple to apply, placing each product characteristic into one of three categories (Kano et al. 1984). "Must-be" or "basic" characteristics are assumed to be present, and customers will be highly dissatisfied without their inclusion. "One-dimensional" or "satisfier" characteristics are linear, in that more of that characteristic will result in a proportional level of increased satisfaction. "Attractive" or "delighter" characteristics are luxury characteristics; customers are not necessarily disappointed if these are absent from a product, but including them can greatly increase customer satisfaction.

Model Overview

The simulation tool was created using the NetLogo 5.3.1 modeling environment (Wilensky and Rand 2015). NetLogo provides an easy-to-use interface creation tool backed by a simplified language for creating agent-based models. As NetLogo is free and open source, the simulation files can be distributed to and modified by students, and it can even be exported to an HTML format that can be used in a browser without requiring users to download the software. A notable drawback is that the NetLogo interface cannot be changed dynamically, and so the number of producers and product attributes are fixed in this model at five each. Fewer than five producers or attributes can be used with the current setup, but the code would need to be altered to allow for additional attributes or competitors.

Each producer sells one product with a static set of attributes, as defined by the user. The expected lifespan of the product is entered separately, which is used in simulating randomly distributed product failure and the need for consumers to purchase replacement products. The consumers have individual preferences for each product attribute, which affect how the consumers rate the utility of each product and make a purchasing choice. These preferences are modified by a random number to account for differing tastes among consumers.

As the simulation runs, each consumer decides whether to purchase a new product. If a consumer does not currently own a product, either because they have never purchased one or their previously owned product has reached its end of life, they will assess their utilities for the products on the market. This operation is based on the assumption that the consumers will always want to fulfill some personal need with one of the available products. It is possible to set up one of the products as a no-purchase option, with the appropriate price, attributes, and lifespan to represent the consequences of not purchasing an available product.

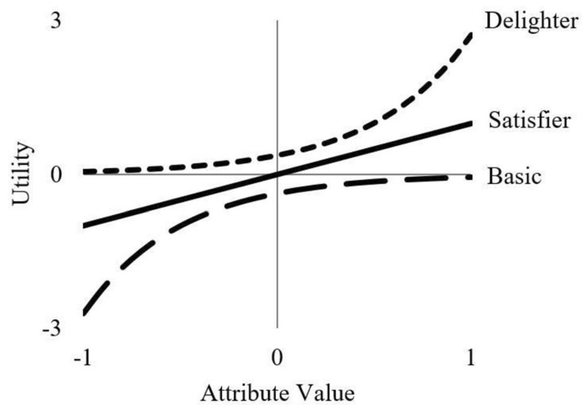

Figure 2. Kano model utility functions (adapted from (Kano et al. 1984)).

Customer Purchase Decision

During the purchasing process, each consumer agent assesses all of the products on the market and calculates the utility of each. The purchasing decision is based on an additive utility function, shown in Eqn. (1). The combination of the consumer's preferences and the product's attributes yields a set of partial utilities, which are added together to determine the overall utility, U.

$$U = \sum_{i=1}^{5} w_i f_i(\alpha_i) \quad (1)$$

Each product has its set of up to five attributes defined by the model inputs, which are represented by α_i. These attributes are used in the utility function f_i corresponding to the attribute's Kano type. The available utility functions are shown in Fig. 2, adapted from the Kano model (Kano et al. 1984). For an attribute considered to be a "satisfier," the utility of that attribute is linearly proportional to the value of that attribute. A "basic" attribute is modeled as a logarithmic function, and a "delighter" attribute uses an exponential function. A "reversed" option is available to represent attributes that have higher utility with smaller numerical values, such as price, which results in a mirror image of the selected Kano type function. The attribute weight, represented by w_i, is entered by the user to linearly scale the utility of each attribute.

Each consumer is assigned a unique set of preference values, which are used in scaling the utility function. The consumer's preferences are the result of multiplying the user-defined attribute weight by a random variable generated at the beginning of the simulation. The random variable uses a lognormal distribution with a mean of 1.0 and a user-specified standard deviation for that attribute. This allows the model to be tuned for the expected level of preference variation for each attribute.

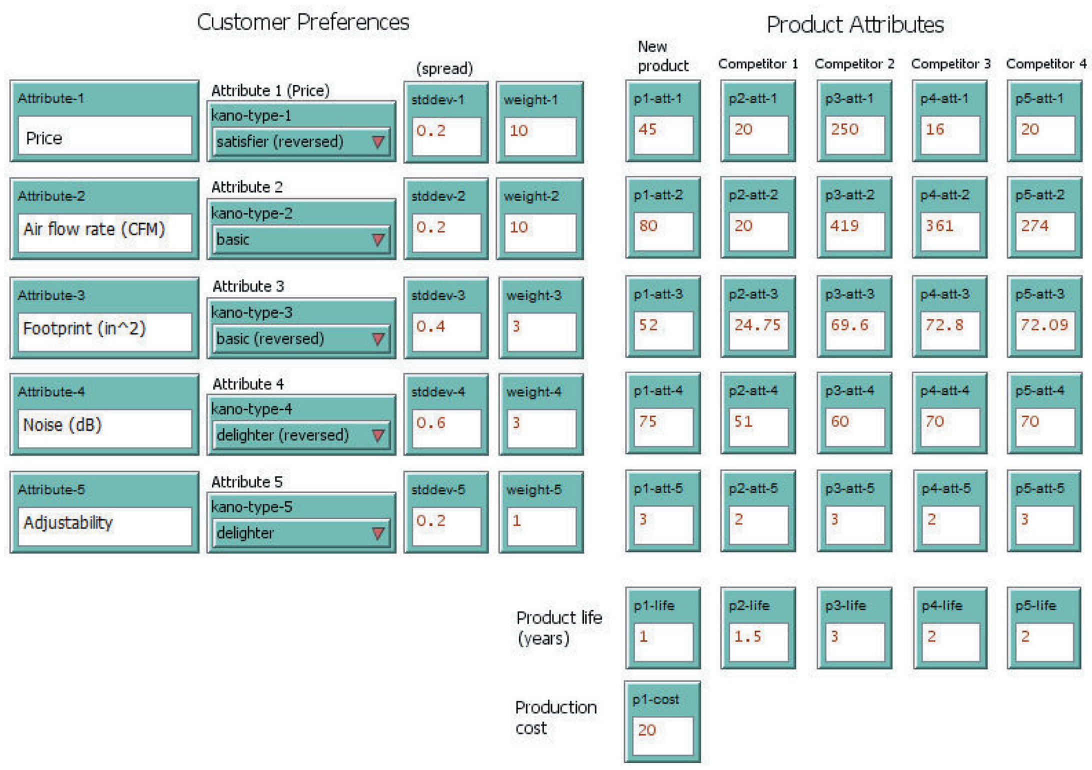

Figure 3. Simulation input for entering product attributes, with values corresponding to desktop fan example.

User Interface

The user interface is divided into two sections. The top section, shown in Fig. 3, is used to input preference and attribute data. Each row represents one attribute. On the left, each attribute's utility function curve types can be entered along with their corresponding spreads and weights. On the right, each product is represented by a column containing its set of attributes. As the intent is for use in a design course with students designing their own product, the first product (column labeled "new product") is the proposed design, and the remaining four are existing competitors in the market. A final row of values is provided for entering the average lifespan of each of the products. An additional input exists for the cost of the new product, which is used to calculate profit values during the simulation.

The bottom section, shown in Fig. 4, contains the output of the simulation as well as controlling buttons and variables. The "setup" and "go" buttons initialize and run the simulation, respectively. There is an option to exclude the new product in the simulation to give students the opportunity to tune the weight and spread values of the attributes to match existing product market shares.

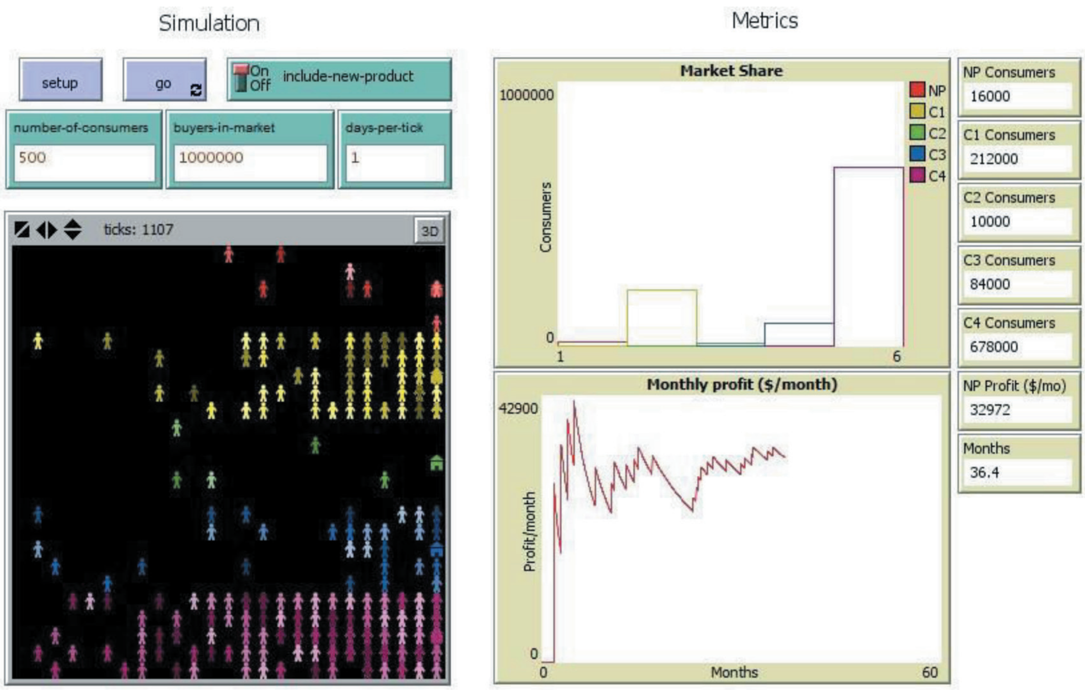

Figure 4. Simulation output display, with user-defined options and results from desktop fan example.

The number of consumers modeled as agents in the simulation is manually entered, with larger counts requiring more time to simulate. The "buyers in market" variable allows the user to represent a large number of consumers with a small number of agents. For example, in Fig. 4, one million buyers are represented by 500 agents, so each agent represents 2,000 buyers in the real market, and a scaling factor of 2,000 is applied to the results. This is faster to simulate but has lower granularity than, for example, using 5,000 agents representing 200 buyers each. Similarly, the "days per tick" variable allows to user to accelerate the computational time by reducing the time-step granularity.

The display on the bottom left of Fig. 4 shows a visual representation of consumer purchases over time. Each product on the market is represented by a different color and region in the display, and each consumer is represented by a person icon. When an agent purchases a product, the agent's color is set to the color of that product. The position of the consumer represents the lifespan of their current product, where the leftmost agents have the longest remaining product life. When the product reaches its end of life, the consumer undergoes the purchasing process again. If a consumer happens to purchase a product with a sufficiently large lifespan, their icon will jump to the left side of the display and slowly move rightward until the remaining product lifespan reaches zero.

A set of output metrics is shown to the right of the display. The top bar chart shows the market share of each product, with the number of consumers scaled to the input market size. The total number of consumers buying each product is displayed numerically on the side of the chart. The lower line graph displays the monthly profit of the new product, with a numerical display on the side.

Using the Simulation

To use the simulation tool, the user must first collect information on the attributes of the proposed and competing products. This information includes the names of the attributes, the type of utility curve used for each attribute, and the attribute's values for each competitor. The spreads and weights for the attributes should be set to a default value (e.g. 1.0) before the model is tuned. The user can then tune the spread and weight values without considering the new product by running the model with the "include new product" switch disabled and adjusting the spread and weight values according to their background knowledge and intuition on attribute importance and variance. These values should be updated until the distribution of customer purchases across the competitors' products achieves a realistic result, using market data, when available, for validation.

Once the customer preference tuning is complete, the new product can be introduced into the model. Students can then see how their product designs will fare in the market they have modeled. The attributes of their product, which include both design attributes and prices, can be changed to observe how these factors affect its marketability. Further discussion among student groups can be held to determine the extents to which their design attributes can be changed while still meeting the requirements of the product. Engineering and cost models should be employed as appropriate to determine feasible attribute combinations. It is important to note that a model developed and tuned in this manner should not be used for accurate predictions, but rather to reveal trends and provide insights on market dynamics and how they are affected by design.

The example used to introduce the simulation to the students in the course was a previous course project to design a desktop fan for personal cooling use. The key characteristics identified for this product market were price, air flow rate, footprint, loudness, and adjustability, which are the example parameters shown in Fig. 4. Many of these values were estimated due to limited availability of information. The model was then tuned while the new product was disabled in the simulation. The Kano types were selected based on qualitative observations by the group during research, and the weights were first set to relative values based on the perceived importance of each attribute and then adjusted so that a realistic distribution of consumer purchases occurred. The spreads were then adjusted in a similar manner. An exemplary observation in this study occurred when researching the noise values for the fan; while a majority of users preferred quieter fans, many users stated that louder fans were preferable for creating background noise, so a larger spread for noise accounts for these differences in preferences.

When the tuning was finished, the new product was introduced to the simulation. Using one million buyers-in-market, the second competitor product (C2) only captured one percent of the market share. This product is considered to be a luxury product, with a very high price and excellent performance characteristics. Most consumers chose to purchase product 4 (68 percent), followed by products 1 (21 percent) and 3 (8.4 percent). The group's proposed product only attracted 1.6 percent of the market share.

The new product's attributes were changed slightly to determine the impact on the product's marketability. Lowering the price did not make a significant difference in customers, as the initial $45 price tag was already much higher than the $16 to $20 price of most of the competitors. Favorable changes in airflow rate, noise, and footprint had a stronger impact on sales. Increasing the airflow seemed to increase the market share the most, which is logical considering the high weighting of the airflow attribute.

COURSE IMPLEMENTATION

Table 1. Engineering Design VI weekly course topics.

W1: Design process models	W6: Concept generation	W11: Prototyping & validation
W2: Design challenges	W7: Concept selection	W12: Production & economics
W3: Leadership & teamwork	W8: Communication	W13: Business planning
W4: Problem definition	W9: Midterm presentations	W14: Design reviews
W5: Market research	W10: Detailed design	W15: Final presentations

To examine the value of the market simulator for teaching engineering design, the model was implemented in a design course for third-year undergraduate students in the Engineering Management program at Stevens Institute of Technology. The course, called Engineering Design VI as it is the sixth in an eight-part "design spine" sequence at the university, is a project-based course that guides students through the product development process, from problem space identification through detailed product design and business planning. An outline of the weekly course topics is provided in Tab. 1, and the learning objectives (LOs) for the course include the following:

- **LO1: Technical design.** Students will be familiar with different methods and tools in technical design and appropriately apply them to develop, analyze, and select design solutions.

- **LO2: Design assessment.** Students will be able to assess the expected performance of designs within the appropriate context and criteria.
- **LO3: Tools.** Students will apply their knowledge of relevant engineering principles and analysis tools to solve complex design problems.

While previous versions of this course focused primarily on design assessment and tools that meet technical performance needs, the course now includes tools in the context of market systems as well. By integrating the market simulator described in the previous section along with accompanying curricular material, the course seeks to provide the students with a stronger understanding of how considering the market context fits into the design process. In the first year of its implementation, the instructor studied the students' responses to the new material through open-ended written reflections and an end-of-semester survey. The survey was approved by the Stevens Institutional Review Board (IRB) under protocol 2017-016(N), and the participants voluntarily signed consent forms prior to execution of the study.

Experimental Design

The simulation tool was introduced to the Engineering Design VI curriculum in the spring semester of 2017, with 25 students enrolled in the course. The NetLogo market simulator was first introduced in Week 5 of the 15-week course (see Tab. 1), after the students had formed project teams of 3-4 students each based on mutual interests in Week 3, and after they had begun to define their problem statements in Week 4. During a 50-minute class session, the students were given a brief overview of market-driven design and the Kano model, along with instructions for using the market simulator. The teams were then instructed to apply the model to their term projects to determine the market feasibility of different potential product outcomes versus existing competitors, based on their knowledge of the product's attributes and information about the existing market. The students were given time in class to experiment with the model and ask questions. Following this, student perceptions of learning were gathered through two open-ended reflection assignments (part of a weekly series of assignments) during the course and a survey administered at the end of the course.

In addition to the NetLogo agent-based simulator, which was used early in the course, an additional survey-based market simulation tool was also introduced later in the course. This tool, Sawtooth Software's conjoint-based market simulator, is a well-established commercial software program that uses discrete choice survey responses to model utility and simulate demand (Orme 2010). Since survey responses were needed prior to using this simulation, it was not used by students for concept exploration until Week 7, and then a second survey was administered for detailed design exploration and simulation in Week 12.

The course is project-based, with 65% of the grade based on team project performance, and each team chooses a unique project topic that matches their interests. As there are no exams or purely objective assignments through which student performance or learning could be compared against the previous year, three different mechanisms were implemented for students to self-assess their learning and provide feedback and evaluate the new simulation tool. Also, due to the authors' expectation that this intervention would provide educational benefits to the students, no control group of students was denied this experience.

Week 5 reflection

Perceived learning was first assessed with an open-ended reflection homework assignment after the introduction to the NetLogo simulator, asking each student to describe their experience, what they learned, and how this exercise differed from what they had done in previous design courses. The prompt for this assignment was:

> *In 300-500 words, please describe your experience using the market simulation tool for market research. What did you learn? What problems did you encounter? Did this help you understand or think about market concepts in a way that you haven't learned in previous design courses?*

This was intentionally open-ended, although it did prime the students to think about "market concepts," with the expectation that the idea of "marketability" would likely show up in many of the responses.

Week 13 reflection

Later in the course, in Weeks 5 and 11, the students were introduced to choice-based conjoint (CBC) surveying, and they conducted two CBC surveys using Sawtooth Software (Orme 2010). When the results of their surveys came in, in Weeks 7 and 12, the students used the Sawtooth market simulator to explore design alternatives using stated-choice consumer preference data, albeit from a limited sample mostly consisting of their classmates. Toward the end of the semester, after the students had experienced the NetLogo agent-based simulator and the Sawtooth conjoint-based simulator to support their conceptual and detailed design decision-making, another reflection assignment asked about both of these tools. This took place in Week 13, using the following prompt:

> *Describe your experience with the market simulation tools (both the agent-based tool from Week 5 and the Sawtooth simulator). Were these useful? What did your team learn? What problems did you encounter? Did this help you think through market and business concepts*

in a way that you haven't in previous design courses? Would you recommend either/both of these in future courses?

Week 14 survey

To elicit more directed and quantitative perceptions of learning value after the exercise, a survey was administered to the students at the end of the semester. This was conducted using paper surveys during class time in Week 14, after all of the course content was delivered and one week prior to the final presentations and reports. The survey consisted of ten questions, the first seven of which were on a Likert scale from 1 (strongly disagree) to 7 (strongly agree). The three remaining questions were open-ended with three lines for short-answer responses. Students were explicitly instructed to consider only the NetLogo simulator in their responses. The survey questions are listed below:

1. My experiences in this class with the market simulator tool have contributed to my ability to design better products. (1-7 Likert scale)
2. My experiences in this class with the market simulator tool have contributed to my ability to analyze product designs. (1-7 Likert scale)
3. My experiences in this class with the market simulator tool have contributed to a better understanding of the role that market research has in successful product development. (1-7 Likert scale)
4. My experiences in this class with the market simulator tool have helped me to better understand the interactions between pricing strategies and design decisions. (1-7 Likert scale)
5. My experiences in this class with the market simulator tool have contributed to my ability to analyze the business case of a new product idea. (1-7 Likert scale)
6. The market simulator tool is useful in the early phases of the design process. (1-7 Likert scale)
7. The market simulator tool is useful in the late phases of the design process. (1-7 Likert scale)
8. What are the strengths of using this type of market simulator tool in a design course? Please try to list around 3. (short answer)
9. What are the weaknesses of using this type of market simulator tool in a design course? Please try to list around 3. (short answer)
10. What additional feedback, if any, do you have on the use of the market simulator tool in Design VI? (short answer)

Results

The findings from these student learning self-assessment instruments were mixed, but encouraging, especially given that this was the first iteration of the agent-based tool and the first attempt to incorporate it into a course.

Week 5 reflection findings

The student responses to the first open-ended reflection assignment were mixed in their general attitudes, and a few notable themes were identified regarding new learning or ways of thinking about design problems. The authors first looked for the overall sentiment of each reflection and classified them as positive, negative, or mixed/neutral. Of the 22 student responses (response rate 88%), 11 students expressed positive sentiment toward their learning experiences with the simulation tool, nine provided mixed or neutral sentiments, and two showed negative sentiment. Regarding the specific market-driven design topics that the students mentioned, three are worth noting: 15 students mentioned that the simulation exercises helped them think about marketability in new ways (which was an explicit, but optional, question in the assignment prompt), ten mentioned the value in thinking through key product attributes, and five mentioned that it facilitated a new way of thinking about competitors. Additionally, 12 of the responses mentioned ease-of-use, with mixed results where seven responses indicated that the simulation tool was intuitive or easy to use, whereas the other five responses indicated that the model was non-intuitive or difficult to use. This shows that there is room for improvement in the user interface and in the course introduction to the tool.

Week 13 reflection findings

After the students had gained more experience with the NetLogo simulator and were introduced to the Sawtooth Software simulator, they were asked for their perceptions of learning and value from both market simulation tools. The responses to this prompt were slightly less favorable toward the NetLogo simulator, as some of the students were more impressed by the capabilities of the Sawtooth simulator. Of the 24 student responses (response rate 96%), 11 students expressed positive sentiment about the NetLogo simulator, six provided mixed or neutral sentiment, and seven expressed negative sentiment. Most of the responses mentioned some particular concepts that these tools helped them to learn, with 11 mentioning key product attributes, nine mentioning marketability, seven noting the competition, and three remarking on consumer utility and/or the Kano model. Four students specifically mentioned that the NetLogo simulator was not easy to use, and none provided positive comments about its usability. Most students expressed their opinion on which of the two tools they preferred, with 14 preferring Sawtooth, six stating that they were equally preferable, and one preferring the NetLogo ABM. Finally, in their recommendations on which to include in future courses, eight students recommended keeping both tools, six recommended keeping only Sawtooth, one recommended using only the NetLogo ABM, one recommended using neither, and five recommended improved instruction for both tools.

Table 2. End-of-semester survey results.

Q	Prompt (1-7 Likert scale, where 4 = neutral)	Mean	Std. dev.	Disagree (1–3)	Agree (5–7)
1	My experiences in this class with the market simulator tool have contributed to my ability to design better products.	4.17	1.77	33%	50%
2	My experiences in this class with the market simulator tool have contributed to my ability to analyze product designs.	4.71	1.81	29%	63%
3	My experiences in this class with the market simulator tool have contributed to a better understanding of the role that market research has in successful product development.	4.96	1.74	25%	63%
4	My experiences in this class with the market simulator tool have helped me to better understand the interactions between pricing strategies and design decisions.	4.75	1.39	21%	67%
5	My experiences in this class with the market simulator tool have contributed to my ability to analyze the business case of a new product idea.	4.42	1.58	29%	50%
6	The market simulator tool is useful in the early phases of the design process.	4.54	1.61	33%	50%
7	The market simulator tool is useful in the late phases of the design process.	4.29	1.86	33%	54%

Week 14 survey findings

The survey results, which reflect the student attitudes toward the simulator and corresponding exercises at the end of the course, also showed an average positive sentiment, shown in Tab. 2. For every question about whether the experience using the market simulator contributed to a certain type of learning, more students agreed than disagreed.

From the short answer questions, the first asked about the strengths of using this tool in a design course. The students listed the strengths of improving their understanding of the following (number of mentions follow each item in parentheses): the general market (7), the importance of features and attributes (7), the importance of competition (6), the role of consumers (6), pricing strategies (3), market viability (3), and general strategy (2). They also noted the strengths in that it is quantitative (2), provides visualizations (1), is engaging (1), and is detailed (1).

The second open-ended question asked about the weaknesses of the tool in a design course context. The respondents listed that they did not believe it to be accurate (5 students noted this), that they did not have enough data (4), it was confusing (4), it was difficult to pick weights (3), and that it had limited features (1). The third open-ended question, and the final question of the survey, asked for additional feedback, to which the respondents mentioned that the tool should be accompanied by better instruction materials (4), have a better user interface and features (4), and that it should be used later in the design process (1).

DISCUSSION

Value for Teaching and Learning

The results from the first classroom implementation of this agent-based market simulator confirm that most students believe it adds value in teaching market-driven design concepts. In both the early-semester (Week 5) and late-semester (Week 13) reflection assignments, more students expressed that they had positive experiences than negative experiences with the agent-based tool. The early-semester reflection assignment specifically prompted the students about whether it taught them to think about marketability in new ways, and 15 of 22 respondents confirmed that they believed it did. Also in the open-ended responses were substantial numbers of students who thought the simulator taught them new ways to think about key product attributes, competition, and consumer utility in new ways.

From the structured survey, at least half of the students agreed that learning took place with respect to all five of the included skill categories: designing better products (50%), analyzing product designs (63%), understanding the role that market research has in product development (63%), understanding the interactions between pricing and design decisions (67%), and analyzing business cases of new ideas (50%). The most value, based on the rating distributions, seems to be present in understanding the interactions between pricing and design decisions and understanding the role of market research. As discussed in the Background section, this self-reported learning is likely more indicative of student motivation and reaction than actual cognitive learning. Therefore, the results suggest that the use of the market simulator and the accompanying curriculum has a positive effect on student motivation and reaction with respect to these market-driven design concepts.

Limitations of the Simulator

It is important to emphasize to students that the simulator is not capable of accurately predicting market behavior. Rather, the simulator was designed to provide students with a platform to explore combinations of product attributes and prices, and how they might affect market shares and profits. It is suitable for use in early-phase design as well as late-phase design, as a model that students can iteratively update as they learn more about the market and the product capabilities. This allows student teams to gain an understanding of the importance of integrating market considerations into design decision-making, and it does so in a more direct way than traditional tools such as the QFD. Effectively, the simulator brings market-driven design thinking into engineering design curricula in an interactive way.

Additionally, while many students in the early-semester reflection mentioned that the simulator was easy to use, one of the major sources of negative feedback was related to deficiencies in its ease-of-use and the instructional introduction to the tool. The recommended next steps include a revision of the tool to improve the user-friendliness and provide active guidance to the user, as well as an update to the instructional design in future courses to include a step-by-step guide on how to use the simulator. The second source of substantial dissatisfaction was related to frustrations and difficulties in determining the appropriate inputs to the model. This could also be addressed through active guidance to the users and improved instructional design. In addition, strengthened supplementary course material related market research and utility models may help clarify and ease the process of finding meaningful market simulation results.

Recommendations

Moving forward, the proposed agent-based market simulator should continue to play a role in this engineering design course, and the authors encourage other instructors to adopt it as well. Most of the students who provided a recommendation of what to include for future cohorts recommended continuing to teach with the new tool, and almost all of those recommended using it in tandem with Sawtooth Software's combined surveying and simulation capabilities. These were viewed by many students as complementary tools, where the agent-based model was more useful earlier in the course before survey results were available, and also by teams who were unable to capture the full market picture in their conjoint surveys. While Sawtooth's conjoint-based simulator was generally viewed as a more powerful tool, the agent-based simulator demonstrated advantages in that it is: (1) able to be used without having to first collect survey responses; (2) flexible for including attributes or levels that were not included in the survey; and (3) free, open access, and available.

CONCLUSIONS

This paper presents the development of a classroom tool to bring market-driven design concepts from the "design for market systems" and "decision-based design" research areas into engineering design education. The developed agent-based simulation model provides a low-barrier, early-phase design tool to interactively teach students about considering market forces in their design projects, allowing them to explore the impacts of different design and pricing strategies on their product's market share and profitability. The tool's first implementation in a third-year undergraduate Engineering Management design course was well-received, and a majority of the 25 students indicated through multiple feedback mechanisms that the tool was a meaningful way to learn about how consumers, competitors, product attributes, and pricing strategies affect their product design strategies. Future work opportunities were also identified to improve the ease-of-use of the tool as well as the instruction that accompanies its introduction in the classroom.

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