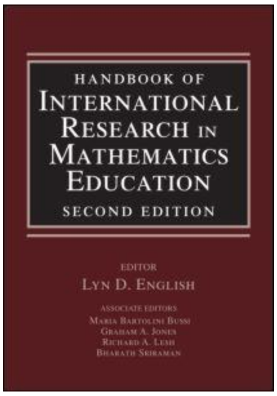

Handbook of International Research in Mathematics Education

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Design research

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Engineering, systems, products, and processes for innovation

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INTRODUCTION

Recent years have seen an increase in the amount of research being conducted under some variation of the term design research (Hoadley, 2004). Our intent in this chapter is to return to the foundations of design research as a perspective for conducting research and examine some of the fundamental characteristics of design in research, evaluation, and assessment. The discussion includes examination of the relationship between engineering and education research in terms of the definitions, questions, and problems that need to be addressed and the means for conducting design. We describe the parallels between engineering and education from a design perspective and draw on examples from recent design projects in engineering education. Both fields can be viewed as applied sciences with the goal of impacting and resolving human problems (Wittman, 1995). In addition, educational products such as curriculum or technology are designed as other products are designed in engineering.

Due to its influence on the educational research community (especially in mathematics education) and the diverse set of interpretations of design as interpretive stance for research, we discuss the roots of design as a perspective for research as well as clarify the parallels between education and the design sciences (particularly engineering). The chapter proceeds in three sections. First, we include a discussion of the background for design research conducted up to this point. Second, we discuss the relevance of design for education and the connections between education and other design fields. Finally, we discuss the complexities and challenges inherent in a design research project.

BACKGROUND FOR DESIGN RESEARCH

Design inquiry has common characteristics. If research is about knowledge development (Lesh, 2002), design research has a role to play both in developing knowledge and developing products for knowledge development. Examples of design research are found in technology (Bannan-Ritland, 2003; Linn, Bell, & Hsi, 1998; Oshima et al., 2004), assessment (Abbott, Reed, Abbott, & Berninger, 1997), and teaching experiments (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Verschaffel et al., 1999) both within mathematics education and in other content areas (e.g., reading). The development of the product and the development of knowledge are intertwined throughout the process. As the product develops, knowledge develops in multiple forms. The knowledge influences later design processes for other products and contributes to the field of knowledge about mathematics teaching and learning. For example, studies have developed particular products but also resulted in knowledge about the design process and principles for future design endeavors (e.g., Bannan-Ritland, 2003; Gersten, 2005; Hoadley, 2004). The authors had evidence about the effectiveness of the product within the context and knowledge to inform the next iteration of the product. Hence, knowledge about process extended beyond the local setting. Design studies, design research, design-based research, and design experiments all fall under the common needs of simultaneous and parallel knowledge development and product development. We will use "design research" throughout this paper to refer to the class of work and investigation where design of a product is a central activity.

Reviews and discussions of perspectives about design research have been published in a special issue of *Educational Researcher* (Kelly, 2003), a special issue of the *Journal of the Learning Sciences* (Barab & Squire, 2004) and a special issue of *Educational Psychologist* (Sandoval & Bell, 2004). Such reviews include contributions from mathematics and science education as well as from experts in other fields that connect with the design sciences. The authors generally have some object they are attempting to design, research goals contributing to theory, and frameworks about teaching and learning. The studies operate at many levels of the educational system from individual students and teachers to groups of students and teachers to larger units of analysis. The products vary and often include multiple components (e.g., connected development of software and a framework for designing software).

Before moving forward into newer applications of design in educational inquiry, we look back at earlier work in design research. Early studies referred to the need for research about learning to shift from the laboratory to the classroom. Ann Brown and others (e.g., Collins, 1992, 1999) borrowed strategies for design from the design sciences as a means of testing methods for teaching in classrooms and moving research out of the laboratory into the classroom via design research. In her case, she was working with reading strategies and how those were used by teachers in the classroom (Brown, 1992). Collins explains how design research can mitigate the gap between research and practice (1992, 1999). Principally, the gap is closed both by the development of research-based products for teaching and the design process as informing disciplinary knowledge. Since Brown's seminal article in 1992 about design in the context of literacy strategies, recent publications have brought out further considerations for design as a perspective for conducting research in education. In addition, the potential for design research to bridge the gap between research and practice has been examined by multiple authors (e.g., Burkhardt & Schoenfeld, 2003; Hoadley, 2004; Wittman, 1995).

In the words of hooks (1994), "any theory that cannot be shared in everyday conversation cannot be used to educate the public" (p. 64). While hooks referred to feminist theory, she discussed the need for education research to bridge the gaps between theoretical positions and the practical needs of teachers and students in the field. Education theory needs to be accessible to the people who ultimately need to implement the products, principles, and procedures that result. In particular, teachers need to be included in educational research and have autonomy as implementers of products (Richardson, 1990). In this sense, one argument for design is that it provides a context for the development of objects and processes that mediate conversation and investigation between the researcher and the teacher (Gersten, 2005; Hjalmarson, 2004). This is not to dismiss the importance of classroom teaching experiments (e.g., Cobb, 2000) or other types of research conducted by and with teachers. There is no reason teacher-as-researcher studies could not be included within a design project. As an example of design work including partnership with teachers, Gersten (2005) described the design process behind a social studies unit related to civil rights. Throughout the process, principles and assumptions related to social studies teaching and learning guided their decision making. The design team included teachers who provided guidance for the design process. The team of researchers and teachers engaged in a series of revisions of their plan and the product based on changing conditions and access to new materials. Gersten concluded with his own learning about the history topic at hand. The results included attention to the process of design and the principles that guided decision-making in the context.

Within discussions of design research, there are two components under review. There is the product under design and the process of cyclic revision of the design. The process and products occur at multiple levels. We have discussed the role of teachers in design research as an example of multiple participants in design. Another type of multiple level design research is the emergence of studies resulting in the development and implementation of design frameworks or other organizing structures as well as the product. Three examples are Bannan-Ritland's Integrated-Design Framework (2003), Clements' work with the Curriculum Research Framework (2007) and Rasmussen's development of a framework for undergraduate students' understanding of differential equations (Rasmussen, 2001, 2006). In all three cases, a tangible product is being developed in addition to a theoretical framework. Also, they include technology as a component of the instruction. Researchers work in partnership with teachers and other types of experts (e.g., in Rasmussen's case, mathematicians). Finally, an organizing structure or framework is developed alongside the tangible product. The framework is applicable to further research and inquiry. Bannan-Ritland's product is a design framework. Clements' framework guides research and design for curriculum with particular attention to scaling-up the use of the product. Rasmussen's framework develops theory about learning in the context. In all three, multiple studies (or sub-studies) are conducted with teams of researchers over time and across sites to influence the design. For Clements' and Rasmussen's curricula, there is also the question of scaling up in the sense of expanding use of curricula and software in multiple contexts. Scaling-up requires implementation training, materials for teachers as well as students, and the development of new products to aid users not directly in contact with the designers or who require modifications for local constraints.

The use of design as an organizer and perspective for research does not eliminate the use of other models for research nor does it imply or discount particular methods. Rather, decisions about methods and focus are guided by the design goals and the examination of the results of the process. The results include both classroom-based products and research-based products to guide future innovations. To clarify some of the possible goals for design, we distinguish some terminology that applies to educational settings. We have selected experiments and research because they have been most commonly used in relation to design. We add assessment and evaluation as new to a design perspective, but long-standing parts of educational research and inquiry.

Terminology

The nature of design work in education has resulted in multiple types and variations of design research depending on the context and the nature of the inquiry. Sorting out the terminology that has evolved is one piece of examining the different roles design can play in educational research. Various terms have evolved to describe a class of educational research activities. Predominantly, there are references to design research and design experiments. What is critical in all the terms is the focus on the design. The "design" is what is being developed, created, tested, refined, and modified throughout the course of the project. As an example, model-eliciting activities were designed for a first-year engineering course. The research team (including mathematics education and engineering faculty and graduate students as well as diversity and women's studies experts) investigated the impact of the model-eliciting activities on the system with particular attention to implications for female students. The activities were compared to other types of activity in the course via surveys and interviews. The students' responses to the activities were assessed and evaluated by teams of researchers. The activities were refined over time as they were tested in the classroom and reviewed by teaching assistants and faculty.

Table 20.1 Types of design projects

Type of project	*Intent or purpose*	*Example question*
Design research	Investigate, study, examine, describe products or processes	What is the nature of students' thinking on statistics-based engineering activities?
Design experiments	Test, hypothesize, compare products and processes	How do different subgroups of students perform on complex, realistic, engineering activities?
Design assessment	Document, justify, summarize, or assess products and processes	What did students learn about engineering statistics?
Design evaluation	Judge, evaluate	How well did the implementation of activities function in the first-year engineering course?

Table 20.1 shows the four aspects of design projects we propose. They have subtly distinct intents or purposes depending on the associated question for the project. The third column lists possible questions that were investigated as part of the engineering project. In all of the types of projects in Table 20.1, the second word is an action on the first: to research design, to experiment on a design, to assess a design, to evaluate design.

The categories are not necessarily discrete. Multiple types of design activity may occur within a single design project (e.g., research and evaluation). We present them as distinct categories here to highlight distinctions in purpose for design activity. The actions or purposes in the second column represent different types of rationale for design activity. For instance, assessing students' knowledge is different than investigating how students' learn. Assessment is part of understanding how students' learn, but understanding how students' learn for research and instruction are different endeavors. What is common to all is a focus on the design (both product and process, both noun and verb). The design is the object of development and creation by the designers for a purpose. Similar to mathematical models created by students that embody conceptual systems in an external representation with a purpose, designs rely on conceptual systems resulting in external representations with a purpose.

In all design sciences, there are artifacts that are external representations of what the designers have conceptualized to fulfill a purpose or need within a context. The products themselves should work within the context as well as informing the design of future products. The design process is a series of design stages of expression, testing and revision over time within the constraints and affordances of the context (Hjalmarson & Lesh, in press).

Why design in mathematics education research?

In the research, we point to as examples in this chapter, there is a focus on the design of an object. We have found that the focus on design processes and products creates opportunities for examining teaching and learning in practice and educational innovation while simultaneously developing innovations (Lesh & Clarke, 2000; Schorr & Koellner-Clarke, 2003; Zawojewski, Chamberlin, Lewis, & Hjalmarson, in preparation). The design process creates opportunities for partnership between diverse sets of experts (researchers, teachers, software developers) for the purpose of accomplishing a goal via the development of some object. The design process is inherently iterative in nature as is teaching and learning. Revision, modification, and extension while moving toward an objective are all part of the design process. For educational purposes, design also naturally incorporates the context for the use of the design. Revision occurs as the objects are tested in practice. Products and processes are not designed in a vacuum—absent of the context or the end-users. The human variables that relate to the context are then included as a critical part of the design. Because of local constraints and the nature of the characteristics being tested in a design, operational definitions may need to be formulated to guide decision-making in the design process.

Operational definitions

Lesh and Clarke describe an operational definition as requiring three components: finding a situation where the construct is evident, sorting relevant from irrelevant information, and determining means for making comparisons among occurrences (2000). They point to the separation between the indicators of a construct and the definition of the construct. Design research and assessment can be used to determine the indicators of student knowledge in a situation that can be used to determine whether or not students understand a concept. For the first component of an operational definition, situation, the design researcher needs to determine when and where a concept may be elicited and how the situation needs to be structured in order to elicit and develop students' understanding. For example, in our engineering work, we asked students to complete tasks where statistics was necessary but did not tell them what statistics to use in order to elicit their understanding of concepts such as variability and distribution of data.

For sorting relevant and irrelevant information in design research, the researchers will likely collect far more data than could possibly be analyzed or used. This process is tantamount to sorting the signal from the noise where in any classroom there can be a large amount of noise (literally and figuratively) that is not relevant to the design research at hand.

Indirect measurement

In order to expand on the development of conceptual systems in a context, we first examine how knowledge about teaching and learning is measured. *Scientific Research in Education* discusses the need for direct measures of educational effectiveness (Committee on Scientific Principles for Education Research, Shavelson, & Towne, 2002). While we agree that direct measurement is part of an educational research endeavor and design research, we also seek to explore scenarios where indirect measurement is needed to quantify qualitative characteristics. We examine, in particular, engineering examples related to the need for indirect measurement. Within engineering there are examples of indirect measurements taken to measure the quality or effectiveness of interventions. One example of indirect measurement is the heating value of natural gas.[1] The heating value is used to buy and sell natural gas in the marketplace. However, natural gas cannot be seen or felt in the pipeline. Measurements of flow, composition, pressure, temperature, and density are aggregated to determine the heating value in order to determine the value of the gas in the pipeline. Flow is measured indirectly with multiple methods such as turbines in the pipeline or ultrasonic measurements using the Doppler effect. Density is calculated using equations of state that are selected depending on conditions in the environment. In short, a quantitative characteristic (heating value) is determined indirectly with quantitative measurements of other aspects in the system. The conditions surrounding the measurement are taken into consideration, multiple measurements are aggregated, and multiple methods used to determine the heating value. The outcome of the measurement answers a financial question about price. In terms of the connection to design research, the engineer is responsible not only for designing the pipeline itself but also for designing the means for measuring (in this case, indirectly) characteristics of the gas going through the pipeline. The types of measurements are determined by prevailing conditions in the system. The measurements have a degree of accuracy (that can be computed) and are aggregated in order to make a final determination. As the object is designed and refined, measurement systems and methods are designed and refined. There are national standards for measurement (e.g., American Gas Association) that determine suitable equations on an industry-wide level for consistency and accuracy.

As an educational parallel, consider measuring the effectiveness of a curricular intervention. *On Evaluating Curricular Effectiveness* points to characteristics of curricular implementation such as implementation fidelity that cannot be measured directly, but rather are characteristics that are measured using aggregate data from multiple sources and measures (Confrey & Stohl, 2004). Asking teachers, "Did you use the curriculum as intended?" is not a sufficient question for determining curricular fidelity. Rather measures such as classroom observation, surveys, and other measures are used to determine whether or not curriculum has been implemented with fidelity to the initial intent of the designers (e.g., Harris, Marcus, McLaren, & Fey, 2001; McCaffrey et al., 2001; Pligge, Kent, & Spence, 2000). In addition, teachers may supplement or integrate a given curriculum with other materials available to them. All such studies carry operational definitions of what is meant by "fidelity" and "implementation" and look for the signs that curriculum and pedagogical strategies are being implemented as intended (e.g., Did the teachers use manipulatives? How were manipulative used with students? What kinds of activities are students engaged in doing?). The measurement methods are refined and developed as the investigation continues. Measurement methods and protocols are also adopted by other investigators and adapted to different contexts. The relationship to the heat index example is that there are a variety of measurement methods, the method selected depends on the context, and the measurements are used to indirectly measure a quality of the system. Means for measurement are developed alongside the product. There is a system of items that work together in relationship to the product design and implementation.

Our use of engineering and design metaphors stems from our experiences working with engineers who often work within systems that are designed rather than isolated products. The constraints of the system impact how the object is designed and implemented in practice. For example, water pumps and valves in a power plant are rarely (if ever) used alone. They operate within a system of other components. Systems engineers are responsible for integrating the components. A challenge in this process is to integrate new components with components that have been designed by other people (who may no longer be available for questioning) at other sites. A second challenge is how to know when to discard a system that is outdated and replace it with an entirely new system. To use curriculum as a parallel educational example, the curriculum is integrated into an existing system of teaching and learning that includes other components. Decisions are made about how to integrate new curriculum in the existing educational system including technology, teachers, parents, existing resources, and old curriculum. Curriculum designers may not be part of the decisions about integration particularly as curriculum achieves wider dissemination. The work of innovation within a system of constraints and opportunities is common both to engineering and education.

The systems aspect is critical since designers interact with the results of other designs developed by people they may or may not know. Consider for example, the design of curricula adopted in school districts that were not part of the initial design team. New design considerations come into play when schools with multiple degrees of separation from the initial design team adopt curriculum. The new curriculum is adopted into a system with existing curriculum, tools, and environmental constraints. The parts of the system need to interact and function even when the players are not all present simultaneously. The complexity in this sense is similar to emergent systems where there isn't necessarily a clear leader directing action. Rather, phenomena emerge over time and via the interaction of multiple players (Holland, 1996). The relationship to design in education is that tools designed in one context are adopted, adapted and refined in another context. Each adoption includes change, new participants, new users, and new needs. The question of scaling up a design is beyond the scope of this discussion, but the role of multiple, unidentified players incorporating innovations into existing systems is part of the question of intervention scale. The systems aspect of design teams also means that different designers bring different types of expertise. In studies described by Hoadley (2004), Bannan-Ritland (2003), Gersten (2005) and others, teachers played a role in the implementation and evaluation of designed interventions. The focus in the design project is not so much on an individual investigator but rather a team of investigators who bring different types of expertise to the table. Establishing partnerships and collaboration between designers on the team can be a long process, but ultimately fruitful and productive if there are complementary or common interests in the product under design as seen in the aforementioned design studies. Beyond the immediate teachers, once a product leaves the initial design context, new teams at different sites or cross-site teams may emerge as the design develops over time.

Relationship between education and engineering

Engineering is another field concerned with systems of interacting parts as seen in the heat index example previously. Our view of design in education research is based, in part, on the similarities and parallels to be drawn between education and engineering as fields which simultaneously seek to advance knowledge, impact human problems, and develop products for use in practice. The two fields are also highly interdisciplinary and rely on results from other disciplines in order to advance knowledge within their own fields. The interdisciplinary nature applies both to the knowledge and to the methods of investigation within each field. Engineering and education are also both concerned with iterative improvement over time. For instance, the last iteration of a product may not be the best iteration for all time. It may be the best iteration for the moment and changing conditions will influence how product quality is evaluated. Engineering and education are both fields about "design under constraint" (National Academy of Engineering, 2004, p. 7). There are human problems under human constraints to solve in both fields. The solving of the problems is accomplished by the design and development of products as solutions. In short, engineering and education share concern for knowledge development in applied fields that integrate disciplines and solve human problems.

As one example of design under constraint in educational innovation, the authors have recently participated in a curriculum design project in engineering education at Purdue University (Small Group Mathematical Modeling).[2] The project intended to design curriculum materials to increase the retention and interest of women in the undergraduate engineering program. However, the project's effects were far-reaching beyond the initial motivation from gender equity. The project investigated other under-represented groups and international students in the first-year engineering program. Effects also occurred for faculty and teaching assistants who began to see their students and their teaching in new ways while also learning about educational research and the complexity of curriculum design. The project also motivated the development of a department of engineering education focused on the development of engineering educators and research about learning and teaching engineering. By introducing a relatively small innovation (the project started with four new activities in one course every semester), significant effects reverberated within the system.

Education and engineering are also fields that negotiate evolving relationships between process and products. The product is designed and then implemented in a system. The process of implementation is a critical aspect of the design relating to questions of feasibility, flexibility, and quality. For example, can a new water pump replace an old water pump smoothly or do other modifications need to be made for the system? What kinds of tests will need to be made to evaluate whether the new water pump is working as well as the old one? Do the users need to be trained? If so, how will that training proceed? These are both questions about the product and the processes that are related to the product. To return again to curriculum, designers will develop materials which require implementation processes raising similar questions to the water pump example. How will teachers be trained to use the new materials? What other parts of the system will need to be updated (e.g., technology)? How will stakeholders know whether or not the new curriculum is achieving intended goals and objectives (e.g., what tests will be used)? The product does not stand alone but rather comes with processes (e.g., training, tests) that are implemented alongside the new component of the system.

DESIGN RESEARCH AS CHALLENGING AND COMPLEX

Design objects

We begin with examples of the relationship between objects engineered or designed in other design fields and examine the parallel characteristics that apply to research about educational objects. First, we identify a set of objects. Then, we examine qualitative characteristics of the objects that can be measured and evaluated (qualitatively or quantitatively). The key point is that the measurement method used to determine quality is dependent on the context and the users. Multiple descriptors may be used in concert in order to develop a complete picture of the quality of the object.

In a doctoral seminar for education students across many disciplines and professions (e.g., teachers, instructional designers, counselors, principals, and administrators) at George Mason University, the students were asked to list items that had been designed in the room where the presentation occurred (see Table 20.2 for examples). They were then asked to describe qualitative characteristics of those objects that would be considered "good." For instance, what makes a "good chair"? The surprising result (even for Hjalmarson) was that the list of qualitative characteristics applied almost uniformly to educational innovations (and curriculum in particular). When substituting "curriculum" for "object," the characteristics in the list could easily be interpreted as measurable attributes of curriculum (or other educational innovations). The other common characteristic across the list of qualities was that they also depended on the context in order to determine their "goodness" as well as their priority among all possible characteristics. This leads to questions of good for whom? When is the object good? To describe the mapping of qualities of objects to qualities of educational innovation, we will explore one characteristic, aesthetics, in more detail.

The aesthetic quality refers to what the object looks like and how it appears to the potential user. As Gladwell describes in *Blink* (2005), chair designers developed an ergonomic office chair that met all the characteristics that a comfortable chair should have. However, the chair didn't look like it would be comfortable and wasn't aesthetically what customers expected from an office chair. The aesthetic characteristics overwhelmed the comfort characteristics in the mind of the customer. For curriculum design, the aesthetic qualities that result from other design considerations may impact the users' interpretation of usefulness or functionality. For example, some of the NSF-funded *Standards*-based curriculum are produced as modules or learning units contained in separate books for students (e.g., *Connected Mathematics*;

Table 20.2 Designed objects, characteristics and questions

Classroom objects	*"Good" qualities*	*Quality questions*
Computer	Functional	Who is the user?
Chair	Sturdy	Length of use?
Table	User-friendly	How much time does it take to learn to use?
Room itself	Cost-effective	Does it integrate with our current system?
Desks	Attractive	Can we afford it?
White board	Effective	Does it fit our purposes?
Television	Strong	Is it multipurpose?
Books	Long-lasting	Is it modifiable?
Objects Designed in Educational Innovation	Sustainable	
	Purposeful	
	Flexible	
Curriculum		
Teaching methods		
Software		
Technology		

Lappan, Fey, Fitzgerald, Friel, & Phillips, 2006). Many other mathematics textbooks put all of the content, units, and problems into one book for students (though this is not a new idea for elementary curricula in other disciplines). While the number of books is a design consideration, it is also an aesthetic question related to what the materials look like. To parallel the chair example, the users may ask themselves whether the books look like what a mathematics textbook should look like based on prior experience with other mathematics books. As a design consideration, having multiple books can increase the teachers' flexibility in terms of sequencing content. With multiple books, the teacher can control which units the students receive and when they receive them. Sequencing flexibility is a design consideration and characteristic not obviously present in other textbooks. Many mathematics textbooks have a linear, hierarchical sequence of chapters and units that does not necessarily appear modifiable or customizable to the needs of a particular learning context. However, a curriculum of multiple books is aesthetically different from a curriculum of one book per grade level, and the aesthetics impact the perceived functionality of the innovation. Similar questions could be asked about technological innovations (e.g., does the layout look familiar to users? Does it work in similar ways to other software?). In Gladwell's example of the ergonomic chair, the designers made modifications to help consumers feel more comfortable about the look of the chair. With time and experience, consumers eventually became more comfortable with the look of the chair. For educational innovation, additional resources and professional development are necessary to help teachers understand how a new model for the appearance of any product is supposed to work including the added benefits to the teacher. With time, users and adopters may become more comfortable with a new "look" for materials.

In the third column of Table 20.2 are a series of questions about quality measurement. The questions relate to the characteristics of objects and have different answers depending on the context and the audience for the design process. While not a comprehensive list of questions, they fall into the broad journalistic category of "who, what, where, when, why, and how." For example, how will we implement the new materials? How much do they cost (in money, time, and energy)? The questions pertain to many objects that are designed or engineered including educational innovations. The questions are both quantitative (how much does it cost?) and qualitative (how well does it work?). Also, constructs used to define quality may change over time. For example, Hoadley reports a change in the design team's understanding and interpretation of "usability" as a measure of quality as users interacted with the technology (2004). The shift occurred as the design team observed students and teachers working with the software and re-conceptualized what they understood as "using" the software. The critical point with any of the questions is that they are situated in a particular context encompassing particular characteristics that may be unique to the setting.

The function of qualitative characteristics in a design research project is to aid the designers in their investigation and development of the product. Answering such questions (based on evidence and data collected throughout the process) helps the product improve based on local criteria and generates principles for design development that may go beyond the particular context. The qualitative characteristics of a design also include the critical questions users may ask when selecting from an assortment of products. Decisions about how to supplement a product (What else do we need to use this?), decisions about how to integrate a product (How does the new product fit into the current system?) and decisions about how to modify a product (how can we improve the product for our setting?) are all questions about quality in the local setting. For design, evaluating the measures of qualitative characteristics, the concepts motivating a qualitative characteristic, and the relevance of qualitative characteristics motivates design revisions and developments. The function, purpose, and goals behind a design motivate the evaluation of measures of quality. The measurements used to determine whether objectives and purposes have been met are a significant part of the research process as the quality of the object is determined.

Design research process

When considering "what works" from the context of qualitative characteristics, the design process then encompasses measuring and evaluating numerous qualitative characteristics and providing evidence of their instantiation in the design context. The focus on a design and its qualitative characteristics then leads to questions about the research process. The special issue of *Educational Researcher* (Kelly, 2003) devoted to the processes of research in design research explored the considerations for any educational research process in light of design methodologies including questions of generalizability, transferability, scale, and method. Frameworks have been proposed as well as illustrations of possible contexts and types of projects. The Integrative Learning Design Framework is an example of a design research framework for the collection of evidence about the design process in order to support claims made about the products and theories resulting from the process (Bannan-Ritland, 2003). The research process is then a process of developing and expanding the framework for understanding the system of learning design. The studies discussed focus primarily on software design, curriculum design, or classroom-based research.

Returning to the theme of challenges and complexities in the research process, the design process has multiple areas of complexity: participants in the process, outcomes of the design, and multiple theories. The first area, participants, is complex because multiple types of stakeholders have different interests in the design product and process. For example, instructors in the engineering curriculum development process had different objectives and needs than the educational researchers. Teaching assistants working with students in laboratory sections of 30 students had different pedagogical concerns than faculty teaching lecture sections of hundreds of students (e.g., consider letting students work in small groups within each context). Each participant in the process from the designer to the teachers to the students has a different investment or need in the product. They also have different operational definitions of "what works." The operational definition of what works leads to the second layer of complexity in the process. Namely, what are the outcomes which measure whether and how well the product is working? How are those outcomes defined and by whom? For a teacher, the question about a curriculum may be about whether students learned the material as intended. For educational researchers, it could be whether the teachers implemented the curriculum as intended with their students. If so, to what degree was curriculum fidelity possible? If not, what prohibited the teachers from implementing the curriculum as intended? Examining implementation should lead to revision of the curriculum.

Reusability, shareability, and iteration in design

Reusability, shareability, and iteration in design are related in that shareability and reusability bear a direct relationship to the iterative nature of the design process. In a design process for curriculum, iterations in the design result as it is shared in new contexts and as different types of users attempt to implement the curriculum. In addition, one curriculum may not work in all situations for all teachers. Clements (2007) claims that curriculum design does not need to result in one ideal curriculum. Rather, he argues curriculum design and research should proceed with consideration given to the conditions under which a curriculum is effective or not. Considering conditions implies a need for iteration within the design process as new types of conditions are used as experimental contexts for the design. Clements also proposes stages in curriculum design that call for refinement over time and the building up of theory as curriculum is developed. For any design process, iteration results as more is learned about the theoretical constructs and conceptual systems underpinning the design.

This moves beyond a question of whether an innovation "works" to a question of when, where, and why an innovation works and for whom. As an example of users refining curriculum in context, consider the use of reform-based curricular materials with his class of urban, Latino, middle school students (Gutstein, 2003). What Gutstein ultimately found was the reform-based materials were effective in some cases and not in others. He generated supplementary materials based on his students' experience in order to explore questions of social justice. By modifying and integrating materials, he could create a cohesive curriculum that made sense to his students and engaged them in mathematical investigation. Even though he did not have fidelity to the reform-based materials, he retained a cohesive, sensible, engaging and mathematically rich curriculum for his students. The example from Gutstein's work relates to other types of educational innovations as well where flexibility is a critical characteristic that can increase the effectiveness of the materials.

In terms of the relationship to engineering design processes, shareability, and reusability are characteristics of system components that need to integrate with multiple systems. A question for the design is whether it is unique to a situation or whether the product could be integrated into a different system? From engineering, consider a system of pumps and valves in a water system. Each component is designed and integrated by different engineers. For example, a set of engineers designed the water pump. Another set of engineers install the pump in a water system after determining needs in the system. Finally, engineers develop testing procedures to ensure the pump is working properly. In an educational context, different sets of people design and assess curricular resources and technological tools, but the materials need to work together in individual classrooms systems designed by teachers. As the engineer adds more components to the system, tests are developed to ensure the system is functioning properly. Teachers, as well, assess whether the system of resources in the classroom is functioning toward students learning. Design research assesses how the system includes the qualitative characteristics described previously and how new components are integrated into the system.

DESIGN AS THEORETICAL PERSPECTIVE

Design research is one perspective on a research endeavor that focuses the study in particular ways. For example, in Hjalmarson's study of teachers' use of assessment tools for problem solving activities, she intentionally chose to focus data collection on the tools teachers used rather than on teaching practices or the characteristics of individual teachers in particular (2004). The design perspective entered into the study in the sense that the questions and data collection procedures were focused on the tools (an external product) rather than on teacher's behaviors in terms of assessment. Rather than assuming there would be one "good" tool, Hjalmarson anticipated that there would be multiple tools for a variety of purposes depending on the teachers' perceived needs for the tools as well as the development over time of new concerns or issues. As the students completed more activities over the school year and the teachers learned about assessment, the teachers needed to respond with new tools. As tools were piloted, refinements were necessary. From a design perspective, the design was introduced into the classroom system, responses were gathered and revisions were introduced (or not depending on the teachers' decision-making). The focus on tools accomplished two goals. First, they were external artifacts easily obtainable that could be used for the investigation. Second, the relationship with the teachers was such that they functioned more as partners in the design of an object than as participants in a research study. They retained ownership of the assessment tool design and both parties (researcher and teacher) had an interest in ensuring that the tools functioned in the classroom environment as well as analyzing the tools afterwards. Design functioned as a perspective guiding the focus of the research and decisions on the data analysis, but other qualitative methods were used for data collection and analysis (e.g., case studies). As a theoretical perspective, design focused the research questions and functioned to delimit the emphasis of the study.

Within our discussion of design and educational research, we employ a three-part definition of a design related to models and modeling perspectives for mathematics education. A design includes a representational system of a conceptual system for a purpose. Note here the emphasis on systems in both representation and conceptual foundations. The definition is derived from theoretical foundations in models and modeling where students develop models to explain, predict or describe a situation (Lesh & Doerr, 2003). In students' mathematical models, they may employ other conceptual systems and experiences relevant to the task at hand. The models also have purposes (someone needs the model to do some task) and representations (e.g., graphical, numerical, symbolic) (Committee on Scientific Principles for Education Research, Shavelson, & Towne, 2002; Lesh, Doerr, Carmona, & Hjalmarson, 2003). Where model-developers utilize multiple conceptual systems and representations to accomplish their purposes, we employ a parallel construct to describe the work of designers (and design researchers). Namely, that designers use multiple conceptual systems and representations to accomplish a purpose. For design research, designers develop representations for a purpose using conceptual systems.

A model in the context of student learning is developed in response to a problematic situation posed by a client. A powerful model not only applies to a particular situation but also applies to other situations. A mathematical model explains, predicts, and describes within the constraints of the situation but without neglecting the need for later generalization. The other powerful piece of the modeling language is that models in many fields are developed progressively, over multiple iterations. Model refinement and modification is part of the process as new information is gathered. Models for environmental systems change with time, more information, and as conditions change. A strong design should accommodate revision and modification. As seen in many curriculum design projects, when different teachers implement curriculum, conditions change. The original developers have little control over how a teacher may supplement or organize materials for teaching. New materials will naturally be modified as they are integrated into an existing system of teaching and learning. A strong design will encourage modification for local conditions. For example, Gutstein (2003) used a set of materials with his urban, Latino students and found that while the materials were strong learning tools for his students, he also needed to supplement the tasks with problems from contexts locally relevant to his students.

PRINCIPLES FOR DESIGN

In any educational research project, generalizability of the results becomes a critical question. *Scientific Research in Education* focused on justification measures for the generalizability of a result or product (Committee on Scientific Principles for Education Research, Shavelson, & Towne, 2002). While situated in local constraints, design research does not neglect opportunities for generalization beyond the local context. Design research examines multiple levels of product generalizability and the construct of generalizability may be different for different levels. The first level is the product itself. In a task designed for an engineering course, the context may be locally defined, rely on data locally available or based on local problems and needs. Hence, the task itself in its final form for the particular class may not be generalizable to other settings. However, at the next level are strategies or principles for implementing tasks. Strategies and methods for implementing and using products may be generalizable across settings even if a particular task may not be. Strategies and methods for implementation can also aid the use of the same task in different contexts and allow for local conditions. As a variation on strategies, we have found in our task design teams that tasks with isomorphic problem statements can be developed but set in different real-world contexts. In the case of both tangible products and recommendations for their use, clarity about the settings in which products are tested will clarify what is and is not generalizable across settings. At the next level are principles for task design that may generalize to different settings. One example of such principles is the six principles for thought-revealing activities (Lesh, Hoover, Hole, Kelly

& Post, 2000). While the principles were initially developed in a middle school setting, the principles were applied in an engineering curriculum design setting and have been applied in other middle school settings leading to the design of multiple tasks for multiple student populations. While a specific task may be locally applicable, the principles behind the task may be applicable across multiple settings. For example, in Gersten's study in a social studies classroom, he describes how the design principles for the learning module guided the decision-making in the design team and helped them evaluate the success or failure of innovations they proposed (2005).

CONCLUSION

Design research is still a new field and examples of research are still underway. It continues to be a means of connecting research to practice, facilitating work with teachers, and examining the development of processes and products over time. As we have discussed, educational innovation is a complex system of interacting components. The complexity arises because all educational endeavors are complex interactions between multiple, responsive components. The components have been designed by multiple designers but must operate in sync with each other. A design perspective seeks to capitalize on the system-based aspects of education as well as principles of design in engineering in order to acquire means for developing and documenting the process of design and implementation of educational innovations. The goal of the design research project is to both develop a product to solve a human problem and to examine processes that accompany that product.

Engineering has been used as the principal metaphor because of our collaborations with engineering educators and because of the parallels between engineering and education as fields of inquiry. Engineering, like education, is interdisciplinary, based on understanding the constraints and affordances of the situation, and open to revision over time. Engineers apply knowledge from other disciplines and integrate systems of interacting parts. The other parallel aspect of engineering is the development of products and the means for testing their functionality in systems of interacting components. In education, this is parallel not only to software or curriculum design, but also to the assessment and evaluation of how the software and curriculum are working. Related to this point is the measurement of qualitative characteristics that are context-dependent. For instance, the user-friendly product in one setting may not be user-friendly in another. Over time, even with the same users, user-friendliness may change (e.g., a teacher using materials for the second time rather than the first time).

In short, we propose a design perspective both for its relationship to engineering and its relationship to complex systems. The design perspective applies not only to research, but experiments, assessments, and evaluations as well. In each of these settings, products are developed and investigated over time. This increases the complexity of the question "How does it work?" and increases the utility of the answer.

NOTES

1. Information about heating indexes in the natural gas industry provided by Lawrence G. Hjalmarson, a chemical engineer and executive in the gas industry (personal communication, March 2, 2006),.
2. NSF Grant No. 0120794

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