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Innovations in Science, Technology, Engineering, and Mathematics Learning and Teaching
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Engineering and Design Research

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Intersections for Education Research and Design

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Introduction

Design research as a methodological stance or a perspective on educational research has drawn on multiple methodologies and theoretical perspectives in education and other fields. In this chapter, we examine a process of research that draws on an engineering view of the process of design. Recent reports (e.g., “The Engineer of 2020” [National Academy of Engineering, 2004]) have described the process of engineering as both an applied science and a means for advancing technical and scientific knowledge. Engineering primarily involves the design and development of products that operate in systems. It includes the process of design as well as the tangible products of design. This interaction between process and product is the similarity between education and engineering that we point to in this chapter.

With each design that enters a system, new designs need to be engineered and old designs need to be refined. The tangible product is only the tip of the iceberg of the engineering process and its relevant results. Throughout the design of a product, plans, conceptual systems, and other intangible products are developed that inform the design of the next product. The intangible products formed during the design process are relevant because revision and extension in the system are inevitable. Consider, for example, designing a digital music player. The first player designed performs a function. When the product enters the system, the designers learn more about how clients use the product in different contexts (e.g., in the car, at work, at the gym), then they revise the product to meet users’ needs more effectively. System integration occurs as the music player works with a stereo system or a computer. Products are seldom used in isolation from other products, and adaptability to changing conditions is needed with subsequent products. As a result, every product will have strengths and weaknesses that will need to be addressed in the next iteration of the design. Evaluation goes beyond identifying a “good” or “bad” product to investigating the circumstances and conditions under which a product is good or bad, useful or effective. Because designs change a system, flexibility and the potential for revision under changing conditions become important.

For education, the design could incorporate curricula, software, technological tools, and other innovations. The design is used in a system (or systems), users interact with the system, and new designs are developed in response to information about the last product and changes to the system. For example, curricula are used in classrooms, data about implementation are gathered in different contexts, standards and assessments may change, and the curricula need revision for continued implementation. Supplemental
materials (e.g., assessments, teachers’ professional development materials) are developed to aid the use of a curriculum. As a curriculum is used, teachers may learn more about their students and teaching and require new types of supplemental materials (e.g., technology, manipulatives). Students learn new information and think about mathematics in new ways that change their understanding of mathematics. The product influences the system and vice versa. The product (e.g., a curriculum) is entering a system where related products from previous iterations have been used already. Throughout this process, knowledge is gained about teaching, learning, and mathematics for the next iteration.

We draw parallels between design in engineering and the design of innovation in education in order to draw implications for research into education. The first parallel is that “engineering is about design under constraint” (National Academy of Engineering, 2004: 7). Constraints in engineering could be financial, material, technical, or political. Constraints also concern the ultimate users or consumers of a product. No one design will work under all constraints and conditions. Rather, engineering design is conducted in reasons, purposes, and conditions unique to a context. Users may not use a product as anticipated (with positive and negative consequences), may not share the engineers’ understanding or interpretation of the situation, or may have expectations for a product not shared by the designers. To return to the curriculum example, teachers using a reform curriculum have used the materials in ways unanticipated and unintended by the original designers because the teachers have different expectations for mathematics teaching and learning than the designers (e.g., Middleton, 1999; Remillard, 2000). The lesson for curriculum designers is how to anticipate better teachers’ use of the materials and to account for the possibility of unanticipated uses. In teaching and engineering, most decisions involve trade-offs among conflicting interests (e.g., time, money, and mandates from higher authorities). Accounting for the trade-offs often requires input from multiple disciplines and perspectives. Economics, science, materials, and technical knowledge from many fields are parts of the final design. In the education field, education, psychology, sociology, mathematics, and practical experience (among other perspectives) inform the use of a design.

Engineering Processes and Engineering Products

Although engineers share some common characteristics, it should be understood that engineering is an umbrella term that covers multiple disciplines. The Accreditation Board for Engineering and Technology lists more than 20 engineering disciplines; among them, long-standing fields (such as mechanical and civil) and more recent fields (such as bioengineering, environmental, and software). All of the fields require their own disciplinary knowledge, skills, and applications that build on and incorporate mathematical and scientific knowledge. Engineering impacts many aspects of daily life. Increasingly, engineering disciplines work across disciplinary boundaries to address design problems. As a result of the diversity of the disciplines and the applications, engineering encompasses the development of a diverse set of products and processes. Although many engineers are responsible for designing tangible products (e.g., electronics, cars, and bridges), another aspect of engineering is the design, development, and refinement of processes and procedures. For example, procedures are designed for the testing of mechanical parts such as pumps and valves that control water flowing through a power plant. The engineer is not designing a particular pump or valve. Rather, he or she develops procedures for testing and gathering data about pumps and valves (products that have been designed by other engineers).
The design of procedures applies to other engineering disciplines such as materials science, where engineers develop protocols for measuring qualitative characteristics quantitatively (e.g., the roughness of a surface or the degree of deformity in a material).

We have found that engineering and other design fields can provide useful ways of thinking about conceptual systems for teaching and design research. The first characteristic is that the process of design is product-driven. The design process occurs for a particular client in a particular situation with particular constraints and affordances. However, the design builds on prior knowledge and experience of design and results in information useful for future designs. The second characteristic of engineering work is that the design is intended to change the environment in which it is used (e.g., to solve a problem identified by the client). Often, this can be translated into a version of problem solving. For example, the design of a portable music player should allow people to take music anywhere. Once the player is available, the system responds with new needs (e.g., connecting it to existing stereo systems, integrating it with a computer, developing new methods for selling music online). When an educational innovation is introduced, the educational situation and context are similarly changed. New design problems may arise. For instance, if new types of tasks or technology are introduced into a class, new forms of assessment may be required, and instructors may want to assess new types of skills and abilities.

In addition to the challenges of carrying out research in a classroom system, there is a gap between the educational theories developed by researchers and teachers’ needs for practical innovations that can be used with students. Essentially, educational practice requires objects to be designed while simultaneously developing and adjusting theories about learning and teaching. From an engineering perspective, this is akin to learning how theories about the properties and behaviors of materials are applied to designing new electronics like a digital music player. Designing new components of the player helps engineers learn about new materials and electronic systems. For education, teachers need curricular materials that are based on knowledge about how students learn mathematics. Researchers need to develop theories about teaching and learning to inform curricular materials. However, it is not enough merely to design one set of curricular materials. For example, when designing materials for a large, first-year engineering course, the use of design principles to develop materials provided grounding for the development of local materials. The principles could be shared with faculty at other institutions who had different local needs, but they could rely on the general design principles to develop high-quality materials.

In a recent curriculum project, statistic tasks were designed for an engineering course. When designing a statistical task, it was not enough to develop one statistics task. The designers also designed clones or twin tasks that employed the same fundamental statistics question in different contexts, and they modified the data sets in order to prevent cheating by students across the many years of the course. For the categorization of students’ work, the same schema could be employed across tasks to understand students’ statistical thinking even though the tasks were superficially different (Hjalmarson, 2004). It is important to know when, where, why, and for whom any educational innovation (e.g., a curriculum, software, or pedagogical methods) is useful and effective. In other words, a design research project should result in the development of a particular product as well as conceptual knowledge that can be used to design future products for other contexts. Hence, aspects of both the conceptual foundation and the design process should inform future work. The interaction between product and process is informed by the language of design.
Design as Verb and Noun

The language of design affords a different perspective on education research than other terminology. One advantage of the use of design terminology in relation to education research is the flexibility of the word itself. We use design as a verb in relationship to the process of design. We use design as a noun to refer to the object under development. Designs are designed. This flexibility in language underscores the ability of design research to document the development of a product over time by investigating simultaneously the usability of the product and the process for developing the product. The language flexibility also brings to the fore the idea that understanding the process of design is as important as understanding the object under design. Research about a design is more than only the final product. Design research is also an investigation into the process of design.

One risk with the language is that it may be unclear whether results pertain to the process or the product. In general, there will be results about both the process and the product. One reason is that a goal of design research is to improve the design process. The tangible product may represent only a part of the desired outcome. Another reason is that the product may be under constant revision and is more often the result of an ongoing, iterative, design revision process than the final result of one cycle of design. To return to the engineering metaphor, as engineers design a digital music player, they should learn about the particular device as well as the design process required for the design of other devices. Thinking about design as a process is conducive to thinking about teaching and learning processes. In a recent curriculum design project in engineering education, the design of new learning units for an engineering course was begun using principles for middle-school activities (Lesh et al., 2000), but it resulted in the development of modified principles for an engineering education context (Diefes-Dux et al., 2004; Moore & Diefes-Dux, 2004). Each design of an educational innovation should produce results for the object itself as well as for the process of design.

Characteristics of Design Research

Usually, designs in engineering and other design sciences are created for complex situations that contain a high number of variables and real-world constraints. Engineering, for example, requires interdisciplinary knowledge and the synthesis of information from many perspectives (e.g., environmental, financial, social, political, mathematical, or physical) (Grimson, 2002; John, 2000). For the digital music player example, engineers need to take into account mechanical, material, and economic considerations because different devices are designed for different purposes and different types of consumers. In addition, “design is a core feature of all engineering activity” (John, 2000: 217). Educational contexts involve a variety of complex interacting systems, and teachers make instructional decisions using a variety of theories (e.g., pedagogical or mathematical). When designing educational objects, multiple theories and methods are relevant in order to explain, predict, or make a decision. One motivation for drawing on many perspectives is the trade-off decisions inherent in the design context and process.

A trade-off decision occurs when variables impacting the design are in conflict. The designer must attempt to optimize and prioritize multiple variables and to justify decisions based on the priorities that have been set. There is room for compromise and the consideration of multiple variables, but sacrifices in one area are made for the benefit of other opportunities. For instance, for a digital music player, the designer should consider size, form, sound quality, and cost as trade-off considerations. A
smaller device could be more expensive, but more desirable for consumers wanting to use the player while jogging. As a result, slightly modified devices are designed for different contexts of use (e.g., for a device to use in a car, size is not as critical as the amount of memory). In a parallel situation, teachers must make decisions based on the time available in a class or the varying abilities of the students in a class. The documentation of decisions about trade-offs aids the generation of theories about teaching and learning by providing information about when, how, where, and why an educational innovation is effective. Documentation also serves later design efforts by providing evidence about what was tried and why (whether attempts succeeded or failed), to inform future design. As in engineering, there are ethical, political, financial, and social constraints that force a designer (or an educator) to make decisions about trade-offs.

To make effective decisions about trade-offs in a design situation, fields that employ a design process use multiple theories and experiences in order to make decisions about designing. The designers’ knowledge and experience come from different sources, both formal and informal. Designing a digital music player includes integrating electrical and computer engineering, materials for the case and the component chips, knowledge about people’s music needs, and economics. To a certain extent, design also entails aesthetic form in light of the function of a device. A device needs to be visually appealing. At this point, design is the art of taking the knowledge available, integrating what is known about the context, and developing a product. For teachers, they must use their knowledge and experience about students, mathematical expertise, personal theories, and information about teaching in order to design a classroom environment that is conducive to learning. There is an aesthetic aspect because teachers consider the form and structure of what they do. Hence, the design of a learning environment is ultimately an integration of multiple theories and experiences. This integration of information from theory, experience, and practice is another parallel between classroom instruction and engineering design.

Iteration in Design

In a complex system, as modifications occur, the system may respond in unpredictable ways. Changes reverberate throughout the system. Iteration in this sense is a process of design, testing, and revision. An idea is expressed or externalized, then it is reviewed and tested. Modifications are made. The idea or innovation is tested in practice. A design is developed and the cycle continues. Iteration occurs naturally in the engineering design process even as students working in teams are learning about design (Hjalmarson et al., 2007).

Iteration is both a natural and a necessary part of design in education and engineering. Just as we encourage teachers to be reflective about their practice, so should designers be reflective about their design. However, reflection does not occur for the sake of reflection. Rather, reflection about design is an assessment or evaluation of the impacts and effectiveness of the design in meeting goals and objectives. Iteration moves in the direction of improvement and refinement, but it is also responsive to changing needs as innovations are introduced. Iteration means improving not only the design at hand, but also the context and system where the design is used.

The role of iteration relates to the use of cycles to describe the design process. The use of cycles highlights the continuous nature of the process, denoting that each phase is not meant to be the last and that design improvement depends on movement based on testing, knowledge development, and interaction between the design and the system where it is used. In the next section, we describe a design research cycle that moves...
between practice and needs while testing designs and developing improvements and modifications that are responsive to a changing system of use.

**Design Research Cycle**

We propose a four-phase design research cycle that incorporates the study of both the process of design and the products designed. As students go through cycles when generating solutions to modeling activities (Doerr & English, 2003), collaborators in design research also go through cycles of expression, testing, and revision of the final product. The cycles are guided continually by the end-in-view for the design research. For instance, one goal could be designing a product that would allow a teacher to understand students’ solution processes for a complex, problem-solving activity (Hjalmarson, 2004). We examine explicitly the interaction between the conceptual foundations for the design of a product and the assessment of its use in a system.

The design research cycle encompasses four phases: the conceptual foundations, the design of the product, a system for its use, and a problematic situation. Each of the phases and the interactions between them are described in subsequent sections. The cycle can be entered at any of the phases and does not begin necessarily at any one phase or proceed necessarily in a linear fashion. Throughout the design research cycle, we emphasize that the endeavor includes characteristics of a design process (e.g., iteration, revision, and testing) and characteristics of a research process (e.g., hypotheses, data collection, description, and data analysis). Design does not occur exclusive of research or vice versa. Rather, design and research occur simultaneously and in parallel for the mutual benefit of both endeavors.

As an overview of the design cycle, we begin with the initial identification of a problem. A problematic situation is the origin of the design issue or the motivation for a product to be designed. A design is required and motivated by something problematic in the context. The problematic situation is the aspect of the context where a problem lies. The conceptual foundation is the knowledge, theory, experience, and conceptual systems that are brought to bear on the process of design. The conceptual foundation is what is known about the problematic situation, the context, the problem, and other relevant theories that inform the design process. The products designed are the tools, innovations, systems, or other designs developed to address the problematic situation, using the conceptual foundation. The system for use is the context and conditions where the products will be used. From the system for use, new problems arise once a design has been introduced. The cycle begins again to accommodate new problems with new conceptual foundations and new products for use in the system. As an example, consider the design of a curriculum for an engineering course. A curricular need is identified in a set of interests (i.e., the problematic situation) that are unmet by currently available materials and resources. Then, the models and principles for a curriculum are identified that might be helpful in the situation (i.e., the conceptual foundation). Next, curricular units are designed with input from multiple partners, consultants, instructors, and experts (i.e., the product design). Finally, the curricular units are tested in the classroom (i.e., the system for use). The cycle continues as new problems are identified.

There should be continuous movement around the cycle. There is also interaction and back-and-forth movement between the four phases of the design research cycle as the product is developed and the design process is documented. For instance, the process of designing the product may require a return to the conceptual foundation and then back to the problematic situation in order to ensure the fidelity of the design to the initial
problem while addressing new problems that may arise throughout the process. This
does not imply that the designers’ interpretation and understanding of the initial situa-
tion remain unchanged throughout the process. Rather, as new information is gathered
and the design proceeds, the designers should check the initial problem situation again.
Throughout the system, documentation of the design process should be collected to
inform future design and the constraints influencing the current iteration of the design.

**Problematic Situations**

Problematic situations motivate the design of a product. The problematic situation
creates a need for a design. The problematic situation encompasses the constraints and
affordances placed on the design, and it can play a number of roles in the design
research cycle. For example, the problematic situation can be the initial starting point
for a design. To illustrate, an engineering instructor determines that the current curric-
ulum does not address the need for students to learn about technical writing and the
process of engineering design. As a result, new types of activities are developed. The
new activities can create new problematic situations (e.g., the need for new assessment
strategies or training for teaching assistants).

The problematic situation relates to an objective (English & Lesh, 2003) because it is
where the problem is identified and the client articulates goals for the design. The
problematic situation is not isolated for the context and it interacts with other aspects of
the system of use for the product. Throughout the design cycle, the designers should
return to an examination of the problematic situation in order to identify whether
the product is meeting the objective, if the new products need to be developed, if the
problematic situation was changed by the design process, and to document how the
needs of the situation have been addressed.

**Conceptual Foundation**

For design research, the conceptual foundation may draw from diverse knowledge
bases, theories, conceptual systems, and experiences. Multiple theories are sensible
when multiple variables impact a design. These variables are not used in isolation from
one another. Rather, they are intertwined in complex ways. The existence of multiple
variables creates trade-off decisions that are addressed by diverse areas of expertise and
knowledge. Similarly, for the designers, multiple theories are used to design any one
product or set of products. Design research seeks to make those theories more explicit
through the products. However, design research requires more than making the theories
explicit. The theories also should be tested in practice by the artifact. For example,
although historical development in mathematics may be used to design a curriculum
unit, the learner may not develop along the same lines as mathematical history. What
may be sensible historically may not be a sensible route from the learner’s perspective.
The artifact tests the theoretical use of mathematical history as a basis for the design of
a curriculum.

Teachers and decision-makers who confront real-life problems naturally use multiple
theories when designing tools for their classrooms. They have to incorporate thinking
from social theories, mathematical curricular materials, school or school district pol-
icies, pedagogical knowledge, and prior teaching experiences when designing a learning
environment for their students. That learning environment includes how students
are asked to interact with each other and the teacher (e.g., How do students collaborate
in groups? How do students share their solution methods?). It also includes the
mathematical topics and the approach to teaching those topics (e.g., How are the topics organized? How are the topics introduced and developed over time? What topics are important? What mathematical skills are important?). In order to answer teachers’ questions about planning activities in their classrooms, assessing their students’ learning, and making decisions about instruction, theories about teaching and learning mathematics need to incorporate these multiple theories and provide products useful in daily practice.

Product Design

The product designed is the object or innovation developed to meet the needs of the user, effect change in the problematic situation, and capitalize on the conceptual foundations relevant to the system. Our purpose in using an artifact or a product as the core of the research activity continues our emphasis on the design aspects of engineering where products are the center of research activity. In addition, different types of products (e.g., curricula) have been designed for many years; however, documentation of the process of design or the effectiveness of such products is somewhat limited. For example, On Evaluating Curricular Effectiveness (Confrey & Stohl, 2004) describes considerations for the evaluation of curricular materials and the types of evaluation that have been completed thus far. Curriculum design processes have lacked documentation to inform future design processes (Clements, 2002, this volume).

Product design generates externalized artifacts that reveal the thinking, interpretations, and assumptions of the designer. It also facilitates future revision. For instance, in modeling activities for students, students generate documentation about the model while they work on the tasks that can be analyzed to learn about their interpretations of mathematical situations (Carmona-Dominguez, 2004), mathematical knowledge, and the development of models (Doerr & English, 2003). The documentation makes knowledge and theories explicit to an observer. Research on teachers and teaching has focused on what teachers do in the classroom (e.g., their behaviors, methods of teaching, and use of a curriculum). However, differences in teaching may be more apparent when we examine what teachers see, rather than what they do, because classrooms are complex systems of interacting parts. As an example, we (as researchers) can see what teachers do in a classroom (e.g., they use manipulatives during a lesson about addition), but to investigate a teacher’s understanding of manipulatives, it may be more important to understand how teachers see the classroom situation when they are using manipulatives for a mathematics lesson (Firestone et al., 2004; Schorr & Koellner-Clark, 2003). How does the teacher see the students using the manipulatives? What is the teachers’ interpretation of the success of the lesson in advancing students’ knowledge of addition? Information about how teachers see the situation may not be apparent in what they do with the manipulatives. In modeling activities, students generally produce a variety of mathematically rich responses. As a result of having new information about their students, the teacher’s view of the students and how they learn mathematics may change. The task in design research with teachers is to ask them to design an artifact that reveals their thinking and expresses their theories about an experience in the classroom.1

1 In modeling activities for students (Lesh et al., 2000), a critical aspect of the activity for revealing students’ thinking is that the activity should be model-eliciting. This means that the task should ask students to construct models that describe, explain, or predict in a specific situation for a particular client in a testable way. For example, an engineering, model-eliciting activity asked students to develop a model for measuring the size of
aluminum crystals using digital images. Students had to determine a sampling method and a method for measuring irregularly shaped crystals (Diefes-Dux et al., 2006). Similar principles apply to design research studies involving teachers; namely, teachers should design artifacts that express their current ways of thinking about their students’ learning in a testable format that can be revised based on the testing. For example, teachers can design products for their classrooms that can be tested then revised based on both their experience in classrooms and the many theories that may be relevant. Designers also develop products that are testable and that reveal the designers’ thinking about a situation. Moreover, testing the products is inseparable from testing the theories that are included in the design of the product. The product and the conceptual foundation should improve and become more robust together. Although a designer may have a prior definition of what will be “good” in a situation, he or she should be open to the possibility that what is “good” in a situation may not be what is expected or what is predicted by the theories. Hence, not only do the artifacts change, but the theories are modified as well. Examples of theory revision based on results from stages in the design process include Gersten’s (2005) examination of a social studies unit and Hoadley’s (2004) discussion of a software design process.

System of Use

The system of use is where the design is tested. The system of use is related to the problematic situation because the problems may arise directly from the system of use. In turn, new problems may arise in the system of use that were not considered in the initial problematic situation. The system of use serves as the principle testing ground for the design. The goals of testing in design research are to advance knowledge about a theory and to develop an artifact that can be used in educational practice (Brown, 1992). The development process for the artifact both informs theory and is driven by theory. The development process is accomplished because the artifact is one representation of a theory, and both are tested and refined as the artifact is implemented in the classroom (Cobb et al., 2003; Edelson, 2002).

Products are tested in the intended context for use and with authentic users. Feedback from the users becomes available to revise the product. The goal in the testing is to document both the usability of the product as well as the modifications that may need to be made. Documentation of usability includes the potential users, the setting, prerequisites for use, and the purposes the product was intended to fulfill. Such documentation is important for the generation of theories because it provides evidence of the process of design. In addition, the purposes for products may change over time as new information is gathered from the setting, the needs of the users are re-evaluated, and the product is tested. Documentation also serves as a record of the theories that impacted the design process.

Because research into design seeks to bridge gaps between research and practice, the system of use is a critical component of the design of educational innovations. First, for design tasks involving teachers’ expertise, the teacher should see a need for the design of the artifact. The need is an outgrowth of practice. Second, for authentic testing of a design, the teacher needs to understand the goal of the design. For example, a teacher designed scoring guides for the assessment of model-eliciting activities for students (Hjalmarson, 2004). The teacher initiated the design of the scoring guides. Hence, the task was personally meaningful for her. As a result of her meaningful involvement in the design of the product, she had a vested interest in testing the design and in understanding what was effective or not about the scoring guide.
Testing in the system of use provides a large part of the data-gathering for evaluating the design. Although other interviews and surveys may augment the data collection, information collected at the site while the design was being tested provides the foundation for the evaluation of the design and the theories underlying the design. Furthermore, clear documentation of the operation in practice provides a trail of information about the design process itself. As mentioned previously, design research provides findings about the design itself as well as the process of design. In terms of examining teachers’ change, the design process can provide evidence of motivations for teachers to change and develop. The design process can illustrate how teachers’ theories about how they teach mathematics change over time as well as the factors that are personally meaningful to them when designing a product for classroom use.

Testing in classrooms includes collaboration with teachers for feedback and input about a design. Teachers provide a connection to testing sites. Teachers provide an alternative perspective on the effectiveness of the design in meeting its objective. Sarama et al. (1998) describe a process of software design that included feedback from teachers and students that was sometimes in conflict. The teachers made assumptions about the students’ interpretation of software that were not completely accurate. The researchers incorporated feedback from many participants and users in order to refine their product. In the process, they developed findings about ways to gather significant input from the teachers about the designs and to convey the purposes and intent of a design to the users. The products were tested in classrooms and refined based on the feedback received. The study included implications both for the design of the software and for the process of introducing it to teachers and using it in schools.

Designers and Other Participants in the Design Process

One aspect of design research involving multiple designers (usually researchers, teachers, and students) is that the eventual users of the artifact (often teachers and students) have input into the design. Teachers, in particular, can function as codesigners who bring expertise about students, classroom practice, and learning environments to the situation. The authors of other chapters in this book (e.g., Zawojewski, Chamberlin, Hjalmanson & Lewis; Bannan-Ritland) explore the practical aspects of a professional development design study with multiple tiers. What we propose here are more general guidelines for design research work with teachers. However, we advocate the collaborative aspects of multitiered teaching experiments. Hence, design research includes many constituents who are all engaged in the design of models (Lesh & Kelly, 2000; Schorr & Koellner-Clark, 2003). While students are designing mathematical models, teachers are designers of models that can be used to explain, predict, assess, encourage, and evaluate the students’ models. While teachers are developing models, researchers are developing models of both the teachers’ and the students’ model design processes. Lesh, Kelly, and Yoon (this volume) and Lesh (2002) describe the interactions between multiple constituencies in more detail. Although this type of interaction between designers is complex and requires careful planning and monitoring, it generates results that contribute both to knowledge about teaching and learning as well as to products that can be used for the practice of teaching.

Individuals can play myriad roles in the design process. In the case of the teachers in Hjalmanson’s (2004) study of middle-school teachers’ design of assessment tools, each teacher played each role in the design process for his or her own tool—as client,
expert, designer, and user. Each teacher identified a problem, used his or her own knowledge and experience about the situation, designed a product, and tested the product in his or her own classroom. In the case of an engineering curriculum design project, engineering education faculty were the clients. Engineering professors from different disciplines (e.g., materials engineering, nanotechnology) were enlisted as consultants for the content knowledge. Education and engineering graduate students worked as designers of the curriculum. Teaching assistants for the large, first-year, engineering course were the users and provided feedback about the curriculum that was used by the engineering education faculty to identify new problems (Diefes-Dux, 2005).

Methodological Concerns

As in any research study, there are methodological questions related to sampling, context, data collection, and data analysis. As Collins (1992, 1999) has emphasized repeatedly, design research is conducive to mixed-method research designs. As in any study, the methods should be selected based on the questions at hand. We reiterate the point that teachers can be collaborators in the type of design research cycles we have described here. Although different types of collaborators may have different types of responsibilities during the project for data collection and analysis, all of the collaborators are participants in the design of the final product and in the design of the methods used to evaluate the effectiveness of the final product at meeting its objective. Bannan-Ritland (2003) describes the interactions between individuals in a design research study where needs are assessed, existing theory is consulted, and theory is generated with product design.

A key point in design research is the selection of the objective to be studied by the designers. The objective should be chosen wisely so that the study results in a product that does what is required of it, but the goal does not depict the specific product. The goal should not limit the nature of the product too much. For example, in Chamberlin’s (2002) study of middle-school teachers, she asked them to design a tool (i.e., a students’ thinking sheet) for organizing the various mathematical methods that students employed to solve a complex, model-eliciting activity. The purpose was to understand the students’ ways of thinking about the mathematical situation. The purpose was specific enough so that the teachers could design a tool to organize the students’ solutions, but not so specific that there were a limited number of ways for the teachers to design the students’ thinking sheets. Chamberlin then could examine the development in the teachers’ interpretations of their students’ work by examining their discussions with other teachers and the students’ thinking sheets. The methods selected for the study were based on the objective and included sociological analysis of the teachers’ interactions.

Collaborators in the design research project should be determined by its goal. If the goal is professional development for teachers, then researchers, facilitators, and teachers are possible collaborators (e.g., Zawojewski, Chamberlin, Hjalmarson & Lewis, this volume). As professional development projects expand, teachers who have been involved at many levels may become facilitators who help design learning experiences for other teachers or serve as teacher-leaders in their school. If the objective is the design of a software environment for teaching particular mathematics concepts, software designers, curriculum experts, teachers, and researchers can collaborate about the design of the software and the design of the classroom environment to support the software.
What Happens After the Design Research?

Design is a continuous process. Although the process has stopping points, we would be naïve to claim that a design is “finished.” Refinements of a design occur in new contexts, grade levels, mathematics topics, or other teaching and learning situations. Refinements and modifications are made to the process of design in new contexts. In addition, a number of tools can accompany a design. For example, in designing curricular materials, there are typically needs for assessment tools, follow-up activities, observation tools, and additional curricular materials. Other directions could include investigation of the factors related to the process of design or the design of related tools. For instance, the principles used to design model-eliciting activities for middle-school students have been applied to the design of activities for first-year engineering students. Although the principles apply to activities in the engineering setting, the principles are interpreted differently for a first-year engineering class than for a middle-school mathematics class. The activities also are designed with the intent of introducing the practical work of engineering. The process of designing an activity includes refining the definition of what it means to do engineering and what it means to help students who have no engineering experience learn about what engineers do. Design studies also should cause designers to be more analytic about other parts of the curricula. For example, in the engineering project, as activities were designed for the first-year course, instructors of sophomore and junior-year courses were re-evaluating their curricula also. The principles for designing an activity were reinterpreted for the courses for more experienced engineering students. Activities were refined as the content became more complex and as activities were developed for specific content areas such as mechanical or materials engineering. The goal of a study that researches design is to have shareable products that can be disseminated to other learning environments. This may involve the scale-up of an innovation. As innovations are scaled up, new methods may be required as the objective changes from implementation in one classroom to implementation across many classrooms. These are only a few of the possible extensions of a design research project.

Conclusions

The parallels between engineering design and education design begin with the nature of the systems where the products of design are used. The systems are not fixed even if they are often stable. The systems require innovation, respond to innovation (e.g., a curriculum, a piece of technology), and are changed by innovation. As a consideration for design, if we think of classrooms as complex systems, then they are systems of complex interacting parts. When the parts interact and innovations are introduced, the systems change, requiring revision or addition to the innovation. When designs are introduced into the system, they should be designed with the potential and necessity for revision in mind. The design process also should account for the nature of the context of use for the design. Not all designs will work in all scenarios (e.g., instructional materials that are designed for different grade levels). Rather, designs likely will need to be modified for changing conditions, new contexts, and different classes of users. However, the design process and conceptual foundation for one product should inform the design of a revised product.

The design process involves cyclic movement between four areas: problematic situations, systems of use, conceptual foundations, and product design. The four stages correspond to movement between theory and practice, knowledge and experience,
design and testing. Throughout the design process, an engineering process involving examination of the constraints of the situation and the needs of the client in light of the conceptual foundations and theory serves to advance knowledge. The final product is more like the nth iteration in a series of revisions than the last product that will ever be designed for a problem situation. Hence, the design research endeavor has results beyond the product itself. The results beyond the product include the principles guiding the design, the knowledge about the situation, and theories connected to the problem situation. This is akin to materials engineering adding to the development of theories about plastics and processes for measuring characteristics of plastics after designing a device. As an educational innovation, curricula designers should learn about curricula design processes, learning, and teaching as curricula are designed. Then, there are at least two products: the curricula and the design process.

Documentation of the design process informs the development of theory and future design. Documentation of the design process explains when, where, how, and for whom a design may be useful and the conditions and constraints under which the product was developed. Beyond the generalizability of the tangible product, the principles and theory behind the design may be more useful to consider in terms of generalizability. Although the product may not be usable under all conditions, the same principles can be used to design products for new conditions. For engineering design, the knowledge behind the design process serves future design efforts by examining what was effective and what was not. The knowledge and principles inform revisions in the complex system of use and the development of products for other contexts. The study results in knowledge about products and their design.

Note
1 See the chapter by Zawojewski, Chamberlin, Hjalmarson, and Lewis (this volume) for more details about teachers and artifact design.

References


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