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Application of Self-Determination and Self-Regulation Theories to Course Design: Planting the Seeds for Adaptive Expertise*

LINDA VANASUPA,[1] JONATHAN STOLK[2] and TREVOR HARDING[1]
[1] *Materials Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA. E-mail: lvanasup@calpoly.edu*
[2] *Olin College of Engineering, Needham, MA 02492, USA*

The paper is grounded in the premise that learning occurs within a dynamic system of social and ecological interactions in the learning environment. Our intent is to open the conversation about how we, as engineering educators, design effective learning experiences for this dynamic system, particularly in light of the deeply ethical, adaptive expertise required of today's graduates. Drawing from two well-researched theories of psychological development (self-determination and self-regulation), we assert that fostering the engagement and positive growth required for adaptive expertise necessitates a holistic educational approach. This approach requires us to consider both the psychological needs of the learner, and the interaction between ecological factors and these psychological needs. We present a dynamic systems simulation model that is based on key concepts from self-determination and self-regulation theory. The model links factors in the learning environment, or 'ecological factors,' to outcomes related to student learning. To demonstrate that the model simulates the observed behavior of the system, we compare model simulations with student motivation measures in three learning situations that were designed and implemented by the authors. The evidence highlights the dramatic influence of ecological factors: high and low intrinsic motivations in different situations, and strong correlations between students' motivational orientations and ecological factors. Comparison of the simulated and measured student responses illustrates the potential for the integrated use of systems dynamics and learning science to aid design of learning environments that foster student motivation, engagement, and learning.

Keywords: holistic; self-determination; self-regulation; adaptive expertise; moral, ethics; learning environment; learning

1. INTRODUCTION

THE PAST TWO decades have brought a wave of engineering educational reform efforts aimed at preparing future graduates to address increasingly complex challenges at the interface of technology and society. There is evidence that engineering graduates from developed nations need domain-specific knowledge and a set of transferable skills in multidisciplinary teamwork, communication, analysis, creativity, business and management, contextual understanding, systems thinking, and independent learning [1–5]. But in addition to these skills, today's engineering graduates must possess personal traits that nurture a deep ethical development, lifelong learning, and a commitment to meeting society's grand challenges. Sheppard et al. observe that

> . . . undergraduate engineering education in the United States emphasizes primarily the acquisition of technical knowledge, distantly followed by preparation for professional practice . . . Concerns with ethics and professionalism, which have new urgency in today's world, have long had difficulty finding meaningful places within this historical model, for not only are programs packed solid with the technical courses, but also there are limited conceptual openings for issues of professionalism [6, p. xxi].

They recommend that engineering educators change their undergraduate programs to include increased emphasis on individual accountability, lifelong learning, and public responsibility, '. . . rather than hoping that students gain, through an experience in a course from another discipline, a deep sense of the complex ethical issues they will face as professionals. . .' [6, pp. xxii–xxiii]. These findings may not be universally generalizable, especially in a global context, but calls for engineering education reform within the global arena serve as evidence that there is a widespread need for change from current methods [7–10]. In essence, these calls for change represent somewhat of a paradigm shift away from engineering as a professional 'end' in itself and toward engineering as a means to an end of professional service to the larger society in which it resides.

We contend that what is needed is a holistic approach to education. It must begin with recognizing that the learner and educator alike are part of an interacting human system that is embedded within the context of a larger society. That is, the learning experience should be designed with atten-

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tion to its dynamic, human, and systems nature. Bransford [11] has made the case for addressing the dynamic nature of learning through developing adaptive expertise—'the ability to apply, adapt, and otherwise stretch knowledge so that it addresses new situations-often situations in which key knowledge is lacking' [12, p. 321]. Adaptive expertise can be viewed as learning in the context of one's professional experience. Bransford suggests that adaptive expertise requires capacities that normally lie at the opposite end of the educational goal spectrum for engineers; they include taking risks, tolerating ambiguity and failure. However, to be consistent with a holistic approach, developing adaptive expertise should simultaneously integrate the human and systems dimensions.

An integrated educational experience aimed at promoting the engagement and personal growth required for adaptive expertise would consider the many factors within the system of the students' learning experiences, and the larger societal system in which it occurs. For example, education studies reveal that classroom social interactions [13–18] have significant impacts on individual engagement and learning. The same can be said of connecting what is learned to meaningful broader contexts [17, 19–22], and the affective state of the learner [18, 22–25]. Accordingly, they should factor into the curricular design. As stated, however, the prevailing focus in engineering education is the technical content of the curriculum [6]. There is an expectation that the professional skills developed through social interactions and consideration of the broader context will come through professional experience [26]. The benefits of integrating these experiences into the curriculum come from recognizing that social interactions around the broader contexts form the basic ingredients for the conditions that foster moral development [27].

Given the complexity of the learning system, designing the engineering learning experience calls for a dynamic systems approach in order to examine how the various factors interact to influence learning. In this paper, we have used a dynamic simulation tool from the discipline of systems dynamics to highlight the interactions between ecological factors (or equivalently, classroom conditions) and the learner. These represent two broad areas of educational psychology that we believe are particularly important for understanding the systemic learning behavior. Our intent is to open the conversation within the engineering education research community about how to holistically design engineering learning experiences. We begin by presenting the two areas of focus—self-determination and self-regulation theory. We then present the dynamic systems model based on empirical research around self-determination theory and self-regulation theory. The model simulates the interactions between the ecological factors, psychological needs and learning. Finally, we compare how the model's predictions of changes in student motivation align with observed empirical data for three learning experiences. These experiences involved the same cohort of students but had very different ecological conditions. The measured motivation trends from students in engineering classrooms are consistent with the model's predicted trends. The model is descriptive of the students' motivational states, rather than predictive. This serves to illustrate the potential of using dynamic simulators as a tool for rethinking how one might holistically design learning experiences for engineers.

2. SELF-DETERMINATION AND SELF-REGULATION—THEORETICAL PERSPECTIVES

Learning is at the heart of adaptive expertise. Self-determination theory asserts that individuals possess an innate drive for learning. Researchers contend that these inherent growth tendencies are tied to individuals' intrinsic motivations, which are catalyzed by a synergistic interplay between psychological needs and supportive environmental conditions. Three basic needs—competence, relatedness, and autonomy—must be satisfied in order to promote learning (see Table 1 for glossary of terms). Specifically, meeting these basic needs fosters intrinsic motivation, engagement, academic performance, and healthy psychological growth [28, 29]. Individuals will engage in learning when given choice and control (autonomy), and learning activities that encourage social connections (relatedness) and foster self-efficacy (competence) lead to greater engagement. In other words, the will to learn is critically tied to the degree to which the learning experience meets the individuals' psychological needs.

However, the extent to which the classroom environment meets an individual's psychological needs is modulated by the individual's personality traits. Black and Deci demonstrate these personality-environment linkages in their investigation of autonomy-supportive college chemistry classrooms [30]. In this study, both students with low and high autonomy orientation at the start of the course showed accelerated development. Both exhibited increased perceived competence, increased interest and enjoyment, lower anxiety, and lower grade-focused goals in response to an autonomy-supportive learning environment. But students with initially low autonomy benefited more from the autonomy support provided through instructor interactions; as these students became more autonomous, their learning performance improved. Black and Deci concluded that classroom environments that support student choice and control contribute positively to the academic and psychological development of all students, but that instructors' autonomy support may be particularly beneficial to students who may naturally gravitate toward the opposite: instructor-controlled environments. In other words, the effect of classroom environment was contingent upon the individual's orientation toward autonomy.

Another key concept in self-determination theory is that of goal internalization, a process whereby learners actively integrate *extrinsic,* or *externally-motivated* goals and behavior into *intrinsic*, or *internally-motivated* goals and behavior. Levels of internalization are described on a continuum with motivational types [31]. At one extreme of the continuum is *amotivation*, a condition that results from learners feeling no competence or autonomy, finding no value in the learning activity, and expecting no desired outcomes. At the opposite extreme is *intrinsic motivation*, a state described by interest, enjoyment, inherent satisfaction, and internalized goals. Intrinsic motivation is also strongly associated with self-initiated and self-directed learning, which are core to what is called *self-regulated learning,* or sometimes *self-directed learning.* Needless to say, *intrinsic motivation* is the desired psychological state in learning situations. Between the two extremes lies *extrinsic motivation*, which is initiative produced by external rewards. As individuals experience greater autonomy and identify more relevance in a task, they internalize the learning goals and eventually assimilate the learning into their own sense of values and identity [28]. When students find meaning in the learning task, they show higher engagement and persistence, improved self-regulation, greater learning achievement, and better social relatedness in the learning environment [19, 20, 22, 31]. Furthermore, Ryan and Connell also showed that internalized reasons for achievement-related behaviors are positively correlated with measures of empathy, moral judgment, and interpersonal relatedness [32]. This underscores the importance of internalizing goals for today's engineering graduate.

Although motivation and goal internalization are required for learning (and by default, adaptive expertise), they alone are not sufficient. Individuals must couple motivation to a set of self-initiated and self-regulated process skills to learn. Self-regulated learning theory addresses the development of these skills. Proponents assert that student engagement is inextricably linked to motivational and environmental factors [33]. It turns out that the same conditions required for intrinsic motivation are also necessary for development of the skills that are foundational to self-directed learning. For example, Pintrich and De Groot showed positive correlations between motivational components (perceived competence, value and interest, and affective responses) and cognitive components (engagement, persistence, and metacognitive and self-regulatory strategy use) [34]. Both Pintrich and Zimmerman propose that the cyclical interaction of personal, behavioral, and environmental factors is the process through which self-regulation is strengthened [18, 35].

Clearly, the classroom climate plays an important role in developing self-regulated learning and skills needed for adaptive expertise. Learner perceptions of the assigned tasks, instructor supportiveness, and social interactions seem particularly important in shaping the self-regulation. For example, Pintrich and Garcia showed that college students' perceptions of autonomy have positive effects on intrinsic motivation, self-efficacy, and task value [36]. Schunk describes how both personal and situational factors such as social interactions influence learner self-efficacy, an individual's beliefs of how capable they are to perform certain tasks. When combined with adequate skills, high self-efficacy can serve as a boon to motivation, behavioral control, and learning performance [37]. Meyer and Turner emphasize that self-regula-

Table 1. Glossary of terms in reference to learning

Construct: a concept that is subjective and not easily measured, such as 'value'.
Self-Regulation: self-generated thoughts, feelings, and actions that are planned and cyclically adapted to the attainment of personal goals [35].
Self-Determination: a sense of choice in, personal responsibility for, and self-initiation of behaviors [29].
Intrinsic Motivation: pursuit of activities for inherent pleasure and satisfaction in doing so, not for external rewards or to avoid punishment [28].
Competence: an understanding of how to perform actions to attain outcomes.
Autonomy: self-initiation and self-regulation of one's own actions; a sense of choice and freedom from external pressures [28].
Relatedness: sense of belonging, connectedness, and safety in the learning environment [28].
Perceived relevance: a sense of connection of learning goals to one's personal context [19, 20, 22, 29].
Value: one's beliefs about the importance or utility of a task relative to his or her own goals [34].
Interest: intrinsic curiosity about the learning topic or domain [22, 34, 38].
Self-efficacy: one's beliefs about his or her capabilities to achieve a desired goal [38].
Engagement (in academic work): individual commitment to learning through the monitoring and controlling of thoughts, behaviors, and feelings. This involves goal setting, application of deep thinking strategies, participation in the social setting, management of time and effort, control of emotions, reflection on learning, etc.
Mastery: attainment of the knowledge, skills, and attitudes necessary for success in a particular learning situation.
Ecological factor: an attribute of the learning environment that affects learning outcomes, e.g., instructor support of student choice, peer and instructor interactions, and connection of learning to broader contexts.

tion is achieved through positive classroom interactions, and that instructors and students share responsibility for relationship building throughout the learning process. They describe how shared understanding between instructor and student may help students set goals, build competence, exercise autonomy, and engage in processes that support their social and emotional needs in the learning process [38, 39].

In essence, the combination of self-determination and self-regulation theories leads to a conceptual picture of the learning process that we have illustrated in Fig. 1. Here, the learner's behavior proceeds from their psychological needs; ecological conditions stimulate the learners' psychological needs and behaviors. This interplay of the ecological factors and their ultimate impact on learning sets the stage for designing effective learning environments. For example, one can imagine that environments that meet their learner's psychological needs for competence and relatedness also foster the individual's capacity to initiate and manage their learning (i.e., 'self-regulate' one's learning). Choice, control, and relevance of what is being learned not only meet the learner's psychological needs, but also can help students learn to initiate, monitor, control, and evaluate their own learning. That is, the same ecological influences that meet the learner's psychological needs also strengthen their ability to self-regulate their learning. In short, meeting psychological needs underlies the development of the will and skill of lifelong learning, a key ingredient in adaptive expertise. Designing learning experiences that aim to meet learners' psychological needs therefore represents a powerful strategy for developing the skills for adaptive expertise and cultivating the classroom conditions for moral development.

3. THEORY IN PRACTICE—SIMULATIONS AND THEIR ALIGNMENT WITH EMPIRICAL DATA

We tested the efficacy of this strategy by redesigning the freshmen, sophomore and junior engineering courses offered within an engineering program at a large public university. The design principles followed a majority of the learning science described above, yet admittedly, not perfectly. In essence, we sought to intentionally manipulate the learning environment to promote greater engagement, motivation, and (ultimately) holistic development. For the purposes of this paper, we show how ecological factors influence one important measure of students' ability for self-regulated learning–intrinsic motivation. We first illustrate how the ecological factors interact to influence learning through a dynamic systems model. We then describe three different learning situations and their ecological factors, compare the models predicted changes with the measured values, and discuss the implications for education.

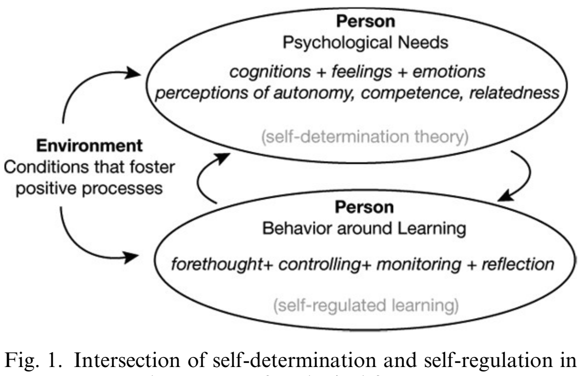

Fig. 1. Intersection of self-determination and self-regulation in the context of ecological factors.

3.1 Modeling psychological needs, engagement and influence of the learning environment

Our model is based on the constructivist theory, which argues that learners must actively construct their own understanding. The theoretical and empirical basis of the connections in the model have been described in great detail elsewhere [40]. The act of learning is 'self-regulated' [35], as described above. To simplify the model, we have collapsed the self-regulated behaviors such as goal setting, initiating, self-assessment, and so on, into 'engaging [in self-regulated learning].' The simple premise is that one cannot learn without engaging in self-regulated learning. This is grounded in the constructivist notion that a learner must internally build his or her own knowledge, an act that requires oneself to regulate. This oversimplification clearly diminishes our ability to differentiate between behaviors such as 'setting goals' and 'time on task'; however, our overarching intent is not accuracy in modeling the myriad of particular behaviors. Our intent is to foster a new way of thinking about designing learning environments through considering the gross behavior of the system and its impact on learning in general. Learning is depicted in Fig. 2, where 'engaging' is a 2-way valve that enables experiences to flow into a reservoir that is labeled 'Mastery.' 'disengaging' (a negative flow of 'engaging') would act as a drain that depletes one's Mastery over time. The cloud at the left side of Fig. 2 symbolizes the surroundings outside of the system. We are only concerned with the system, not the surroundings. Mastery is used here to refer not to expertise, but to proficiency or understanding in a particular learning situation. Together, engaging and Mastery represent the process and result, respectively, that is generally called 'learning.' We view the behavior around learning through the lens of self-regulated learning theory (Fig. 1, bottom oval, 'Behavior Around Learning'). Fig. 2 represents a simplified picture of the aggregated behavior around learning.

We will next consider the learner's psychological needs (Fig. 1, top oval, 'Psychological Needs') and how they influence learning, which we present through the lens of self-determination theory. In this model, we limit our consideration to six basic

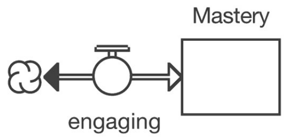

Fig. 2. Engaging in learning builds mastery.

psychological needs as shown in Fig. 3, beginning with autonomy (1), interest (2), and value (3). These are the primary inputs to the learner's intrinsic motivation (4), modified by their self-efficacy (5) and social relatedness in the learning situation (6). Educational psychology studies suggest that these and other psychological traits develop in the learner through situational experiences. We chose to model this phenomenon as valves that allow a flow of situational experiences into rectangular reservoirs as depicted in Fig. 3. In the language of system dynamics, the reservoirs represent a stock and the valves regulate flows. The reservoirs represent psychological *traits* that are generally stable over time, but may vary in differing contexts or situations. Traits are differentiated from *states*, which are situational or transient. Self-efficacy and social relatedness, two psychological states, are represented as circles or 'converters' that will modify the flows into Autonomy, Interest and Intrinsic Motivation. Note that the flows are activated by two-way valves, indicating that the flows can fill or drain their reservoir. Each reservoir is like a bank account, with the situational experiences constituting the deposits or withdrawals to the account.

In Figure 4, we depict the reinforcing effect of situational experiences. Arrows indicate that the flow at an arrow's tail (○) influences the flow at the head of the arrow. For example, one's *perceived relevance* of what is being learned boosts their *situational interest*, which in turn boosts their *situational intrinsic motivation*. Notice that we also indicate that the perceived relevance of what is being learned directly influences the situational intrinsic motivation to emphasize the critical role that relevance plays [19]. The plus sign at the head of the arrow indicates that the two flows are positively correlated. That is, increases result in increases and decreases result in decreases. If the learners' believe they are capable and have the option to freely choose, their interest and motivation in the learning situation increases. In other words, if their level of self-efficacy matches the level of autonomy in the situation, they will be both more interested and motivated. This is reflected in the model by modulating the impact of the situational autonomy with the level of self-efficacy, which appears as an arrow going from the situational autonomy to the self-efficacy, and two arrows emanating from self-efficacy into situational interest and situational intrinsic motivation, respectively. This modulating impact of self-efficacy underscores the importance of providing the appropriate range of freedom to learners. Some students, given complete freedom to compete an assignment, will feel overwhelmed by the lack of more specific guidelines, or by the lack of belief that they can complete the goal.

In reality, we do not know if, for example, perceived relevance literally 'adds' to situational intrinsic motivation or multiplies with any of the other inputs to situational intrinsic motivation. In this model, we have used a conservative approach, treating all inputs as additive. Again, we are not seeking predictive accuracy with respect to the absolute values of the various flows and reservoirs, but the relative time-dependent behavior and interaction of these quantities for different learning environments.

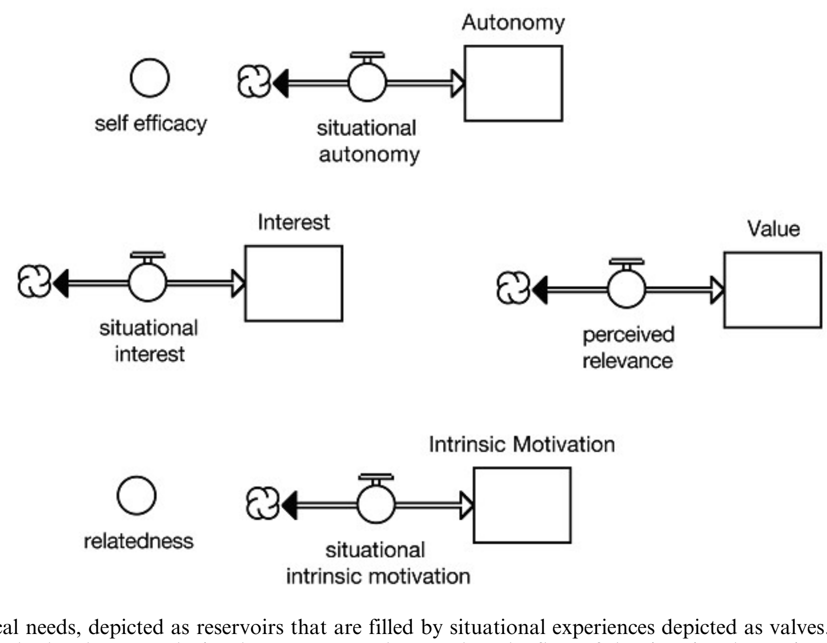

Fig. 3. Psychological needs, depicted as reservoirs that are filled by situational experiences depicted as valves. For simplicity, self-efficacy and relatedness are depicted as converters that regulate the flow of the situational experiences (valves).

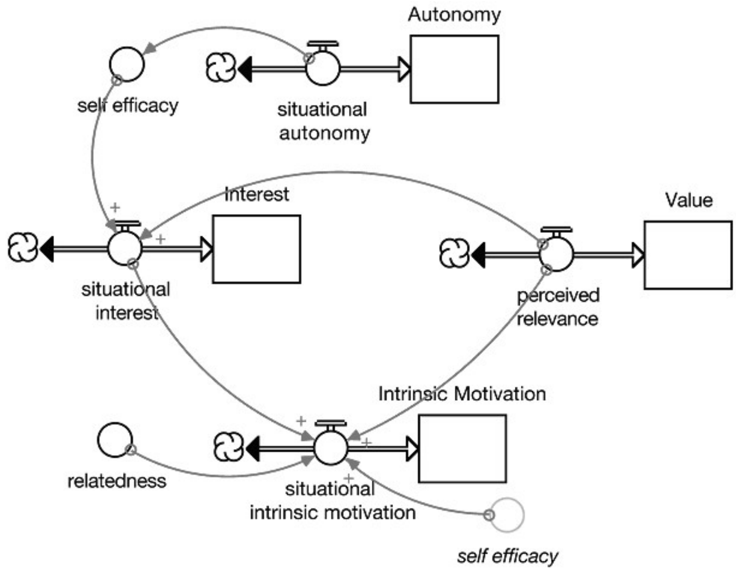

Fig. 4. Situational experiences reinforce one another. In this image, *self-efficacy* shows up as a 'ghost' at the bottom right for the purposes of image clarity.

When the psychological needs (Fig. 4) are coupled with self-regulated learning (Fig. 2), we have the situation depicted in Fig. 5. Note that Fig. 5 is a systems dynamic depiction of the conceptual model in Fig. 1 with the square frames (Fig. 5) equivalent to the ovals of Fig. 1. Here, the behaviors collectively called *learning* are grouped within the frame called 'Behavior Around Learning.' As shown, engaging is promoted by the situational intrinsic motivation, the perceived relevance and the learner's self-efficacy in the situation.

Now we turn our attention to the ecological factors in the learning environment and the personal traits of the learner. For the purposes of this

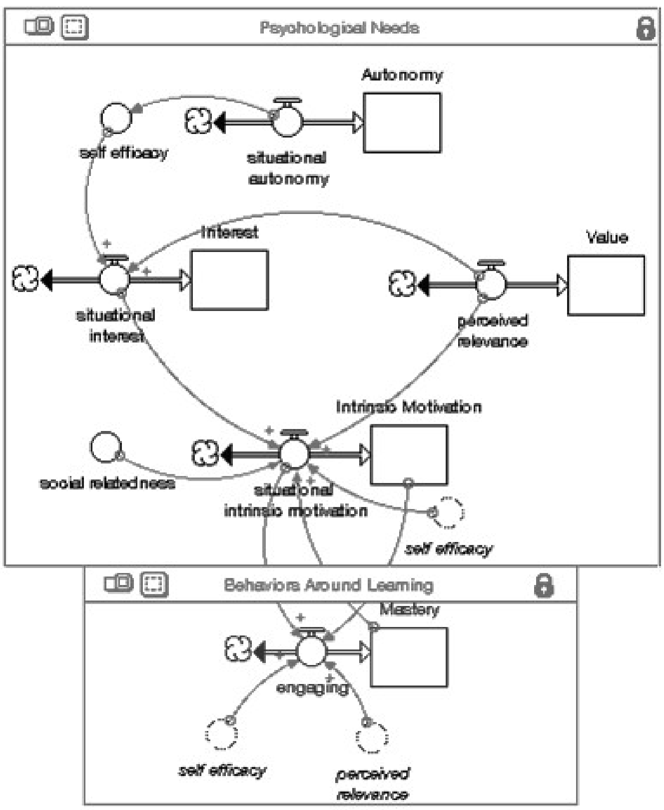

Fig. 5. Links between psychological needs and self-regulated learning behavior. Note that most of the psychological needs affect mastery through the learner's choice to 'engage' in learning. However, self-efficacy and perceived relevance also directly influence engaging.

paper, we include three salient ecological factors. They are *freedom of choice, social relatedness support,* and *explicit connection to broader contexts.* These factors influence the psychological needs of the learner, which in turn will influence their engagement in learning. The way in which we have included them in the model is depicted in Fig. 6. Fig. 6 is the system dynamic model version of the conceptual model of Fig. 1 with the *ecological factors* interacting with *psychological needs* and *behavior around learning*. As shown, social relatedness support is positively correlated to relatedness. Relatedness broadly encompasses the learner's sense of safety and belonging in the learning environment, which includes the impact of peer-to-peer interactions as well as student-faculty interactions. Explicit connections to broader contexts increase the perception of relevance of what is being learned. These connections answer questions like, 'How does this relate to situations other than this? How does this relate to me as an engineer? How does this relate to peoples' everyday lives?'

Students' engagement is also influenced by the extent to which students have freedom of choice. However, it is possible to give too much freedom, in which case, the students' can feel a sense of high anxiety or defeat, not knowing what to do or how to do it. This is depicted in our model through the interaction of the freedom of choice, self-efficacy, and what is called the learner's zone of proximal development (ZPD) by Vygotsky [41]. In this model, we categorize the ZPD as a personal trait of the learner. The ZPD conceptually represents a learning zone within which the learner is able to independently learn or acquire the skill with the aid of a peer. To our knowledge, no one has developed measures for the ZPD.

Vygotsky proposed that the theorized ZPD varies from individual to individual. Like 'self-confidence,' the ZPD is a personality trait that theoretically can be measured through specific beliefs, attitudes and behaviors. For example, students with a large ZPD would theoretically be likely to report high confidence in their ability to address unstructured problems, a high level of interaction with their peers as learning resources. A small ZPD implies that the student needs a great deal of guidance and is less suited to self-directed learning. Giving extensive freedom of choice to someone with a small ZPD would overwhelm them, resulting in decreased self-efficacy. In this situation, a student may look to external motivators, asking questions like 'What do I need to do to get a good grade in this?' In essence, their goals shift away from learning and towards surviving. As indicated by the connecting arrows, a decreased self-efficacy would decrease the learner's situational interest, situational intrinsic motivation and engagement in learning. In contrast, a learner with a high ZPD will have a high level of self-efficacy for assignments with a large freedom of

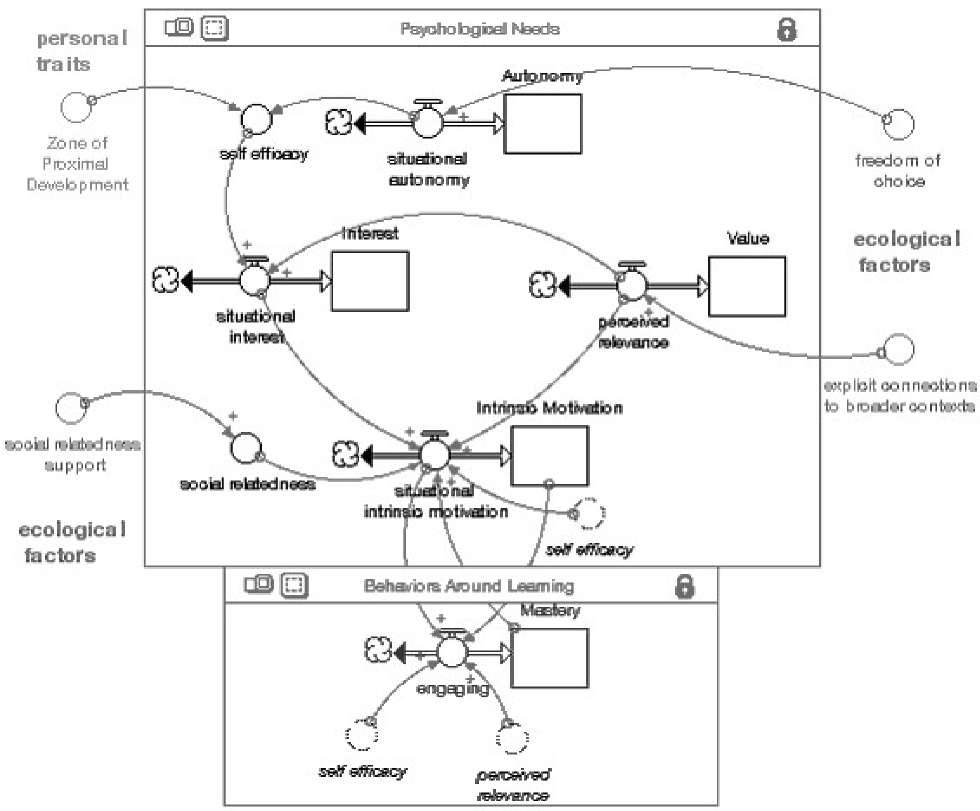

Fig. 6. Influence of ecological factors.

choice and thus thrive. However, if the learning situation is very constrained (low freedom of choice), a learner with a high ZPD can experience decreased self-efficacy because a highly-constrained assignment robs them of the opportunity to self-select goals, an important contributor to goal commitment and increased self-efficacy [37].

3.2 Applying the model to the three learning situations

The model considers the interactions between psychological needs and ecological factors. Using these ecological factors, the model can dynamically evaluate motivational and behavioral responses to environmental stimuli and predict whether their net effect nurtures or inhibits learning. Its dynamic simulation form, which essentially represents the time-dependent behavior caused by the multitude of interacting factors, was developed after the courses were designed and the data were gathered. We would like to emphasize that its value is in illustrating impacts caused by the dynamic interaction of factors in the learning environment; that is, it is valuable in showing trends. It is not our intent to assert its capability for predicting absolute value changes in student learning constructs.

In this section, we compare the model's predictions to measures of student intrinsic motivation in three different learning situations. Each of the learning situations involved the same cohort of students; however, the situational and ecological factors for the situations were different. Our primary goal is to examine if the model predicts increases or decreases and whether the data aligns with the expected change. In the following sections, we first provide a description of the three different learning experiences and then describe the relative quality of three ecological factors for each of the experiences: *freedom of choice*, *social relatedness support*, and *explicit connections to broader contexts*.

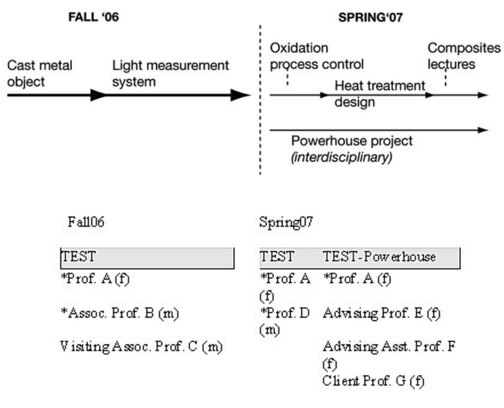

Fig. 7. Faculty data for the TEST cohort in the Fall and Spring learning experiences in courses within their engineering major. The faculty gender is indicated by f (female) or m (male). Leading or co-leading instructors are indicated by (*). In the spring term, the Powerhouse project was completed in parallel with the process control and design projects.

3.3 A detailed description of the learning experiences

The study involved a group of junior-level engineering students at a moderately large (~20,000 student population), public, primarily undergraduate institution. The test group of students participated in an engineering curriculum that emphasized student control and choice in many aspects of the courses and was organized around themed projects. One of the seven faculty involved in the teaching and advising of the courses (Professor A, Fig. 7) was a faculty for both the fall and spring terms. There were significant differences in the preferred teaching styles of the faculty for the fall and spring experience. For example, Visiting Associate Professor C (male) in Fall 2006, was very comfortable with the ambiguity encountered in design projects. Professor D (male) in Spring 2007 preferred controlled problem-solving settings with clear right and wrong answers. These stylistic preferences came through in the course. For modeling the impact, we have captured these stylistic differences largely in the ecological factors.

The learning experience of the test-cohort was designed to address several facets within the self-determination and self-regulation theories while imparting core engineering science principles. Students were involved in a year-long series of junior-level courses in their major that were organized around engineering themes. These students met with the instructors for the course for 12 hours per week, usually in 3-hour blocks on four different weekdays. Lecture and laboratory modes were mixed so that the activities within the class could be suited to the learning needs. As a rule, the class time activities were designed to minimize the formal 'lecture' time in the fall course to 10–20% of the time. In the fall, the test cohort focused on two different team projects: designing, building and testing a fiber-optic light measurement system and designing, prototyping and marketing a cast metal object to an environmentally-oriented client. In these projects, instructors played the role of clients and were interviewed at the beginning of the projects by the students as part of the design process. The projects were completed in series. The details of the design were artificially constrained in ways that forced certain topics to be addressed in the design. The students worked in formal teams that lasted the duration of the term. Six teams of six students each were randomly and openly organized by the instructors based on an even distribution of students' self-reported strengths in the areas of communication, electronics, machining, CAD, creativity and mathematics. Once assigned, the student teams collectively negotiated with one another the weighting to be used for their graded work in the course. The limits of the weighting were set by the instructors and included a balance between team-grades and individual grades. This procedure, developed by Michaelson, Knight, and Fink [42], was intended to ensure individual buy-in, foster teamwork and provide freedom of choice.

During the projects, students utilized a formal engineering design process, starting with user needs assessment, proceeding to conceptual design, development of functional requirements and design specifications, engineering design, prototyping, building, testing, and reporting the results. Project teams presented their work in concept and final design reviews, and each student submitted a written report at the end of the project. The project involving the cast metal object was conducted in a similar fashion. Four separate activities were interwoven into the course in a way that illuminated some phase of the design process, while also educating students on the fundamental engineering science concepts. For example, students completed a 6-hour project that required them to cast metal alloys into different molds, and characterize the resulting microstructure. This activity included a guided-inquiry worksheet that lead them through the fundamentals of nucleation and growth and enabled them to connect the microstructures to materials science theory.

While the students were given autonomy in the design process, the level of autonomy was constrained by the physical and economic resources of the program. For example, in the casting project, the selection of materials was limited to a small set of alloys that could be processed on campus, the design geometry was tightly constrained by the casting setup, and analyses of the cast products were limited to testing devices available in the materials laboratories. Even though some of these restrictions were unique to the educational setting, the existence of constraints gave students experience in designing with constraints. The instructors made every effort to provide an authentic feel to the projects, drawing upon industry-relevant standards and practices, and emphasizing professionalism in reporting.

During the spring term, the test cohort, which had changed by six students, worked on three team projects. Two were similar to the fall experience; however, the focus was on process design and control, rather than on designing an engineered product. Additionally, students were given significantly larger autonomy in completing the project, including selecting their own teams. Learning materials were available in binders with self-paced, self-assessments. At the end of the term, students were given somewhat more traditional instruction in composite materials for a two-week period. Both instructors were available for assistance. The third project, dubbed the 'Powerhouse project,' involved eleven teams, each consisting of engineering majors (3 students) history majors (1 student) and art and design majors (1 student) and a real client. Teams were assigned by the instructors. This project was completed in parallel with the process design and control projects. Unlike the design projects in the fall, the Powerhouse design outcome was not defined clearly. Instead, students were given a list of eight functional requirements for the final product (Table 2). The goal was for each team to present a design and concept for the internal space of a building that was the original powerhouse for the region. This building was on the state's historic building registry and the client was attempting to obtain government funding for converting the space to a museum/educational venue. The Powerhouse groups met weekly with their non-engineering major counterparts to make progress on the design. The instructor established the design timeline and built two design reviews into the 10-week process. Only two of the 12 hours per week of formal class time were allotted to the Powerhouse meetings.

Table 2. Functional requirements of 'Powerhouse' project

1. Project must tell a story that weaves together historical, cultural, technological themes about energy in California (past, present & future).
2. Project must relate to the Powerhouse.
3. Story must be supported by quantitative and qualitative evidence.
4. Sources must be documented.
5. Must be compatible with Powerhouse display space.
6. Must specify and address a specific time period of significance.
7. Display design must embody the principles of the project.
8. Must be appropriate for "informal science education" audience.

Throughout the term, faculty took ethnographic data on the interactions of student teams. Students were not aware that they were being observed. Additionally, the history and art and design faculty advisors met weekly with the students and recorded field notes of the conversations. Thirty-nine of the 56 students involved in the Powerhouse project also participated in semi-structured exit interviews after the course grades were assigned Nineteen of the 39 were non-engineering majors.

3.4 Relative ecological factors for each of the learning experiences

Following approval for human subjects research at our institution, we gathered data from student cohorts involved in the study. For these different learning experiences, we estimated of the ecological factors that existed in the classrooms (Table 3). Our intent was to use the estimates to compare simulated trends with student measures. The estimates are based on a combination of survey responses, course evaluations, interview responses and field notes. For example, in the post-interview for the Powerhouse experience, one of the emergent themes from students of all majors was the difficulty in team collaboration caused by the different disciplinary perspectives. The non-engineering students described these difficulties as increasing near the end of the project when the pressure to produce increased in private meetings with their faculty advisors. In the semi-structured interviews, the difficulties were expressed by engineering and non-engineering students in reference to the different disciplinary mindsets. The following student comments provide two examples:

Non-engineering student: I wouldn't call [working with engineering students] difficult. It – it's mostly to do with how different the, um, mentalities of a certain field are – a certain discipline are. Just by the – for one thing, by the way they're just made. Our – our – our students usually just think differently from Engineering students by default. . . . And then also from the kind of classes they take and from the kind – the way that they were – they're trained and drilled to think. They – they think a certain way. And it's just – it's just like a clash of really – of polar opposites, really – when graphic – graphic artists and engineers comes to – come to work together. And usually it becomes difficult, um, when the engineers kind of – I wouldn't say they – they refuse, but it's difficult for them to step out of kind of their – their really linear perspective

Engineering student: A lot of times I found that some people – I mean, like, saw the project in different ways – And that made it really difficult. And, ah, I think the key thing is communication. So I think an ideal situation would be able – to be that everyone could convey their convey their message well. You know, could say what they want to say where everyone else understood it. 'Cause sometimes – I mean – I know in a group setting it's hard to get your – what you want across – or get your, you know, idea across. . . . – so it's hard to – it's definitely hard to communicate with people who don't think the same way you do.

Initial observations of classroom interactions of the Powerhouse teams confirmed that the teams were initially enthusiastic (Weeks 1 and 2) and then increasingly less so. We chose to model the *relatedness support* as starting high and decreasing to low levels as the term continued to reflect the increasing difficulty of the team dynamics as the term progressed (Table 3, POWERHOUSE, *Relatedness support* = Decreasing to low values).

Students in the Powerhouse project also described what they felt was confusing and conflicting messages from the client during the mid-course design reviews. Some groups described this as so disorienting that they started their design process over. Many students, particularly those in engineering majors, mentioned their disappointment that the assigned project seemed irrelevant to their post-college careers. Professor A did not intervene and make the connections more clear for the engineering students during the project. This experience was modeled as POWERHOUSE, *Connection to broader context* = Decreasing to low levels (Table 3). Because students had nearly complete freedom to design the Powerhouse project outcome, if was modeled as POWERHOUSE, *Freedom of choice* = Very high (Table 3).

For the Fall 2006 TEST experience (N=36), the social relatedness support was deemed high because they reported extensive interactions with peers as learning resources on a five-item survey based on the work of Knowles [43]. The survey included the following statements to which the respondents could state that they agree, somewhat agree, are unsure, somewhat disagree, or disagree. The statements were: (1) I am able to relate to peers collaboratively; (2) I see my peers as resources for helping me plan my learning; (3) I see my peers as resources to help me know what I need to learn; (4) I see my peers as resources for my learning; and (5) I give help to and receive help from my peers. A t-test of the means indicated that only the mean response for item 5 was significantly higher than that of their peers ($p < 0.05$). However, we note that the TEST cohort's (N = 36) means for items 1–4 were also higher with p-values 0.08, 0.57, 0.53, 0.19, respectively. In other words, students reported a significantly higher level of interactions with classroom peers as learning resources (item (5)) than was reported by their peers (N=19) in traditional curricula. We speculate that the small sample size for the quasi-control group is in part responsible for our inability to discern statistically significant results within the other four items.

We used students' self-reported high level of peer-to-peer learning and their responses to the Safoutin Design questionnaire [44] (Table 4) to infer a relatively high ZPD (Table 3, all experiences: *Zone of proximal development* = high). Recall that the three learning experiences involved the same cohort of students in different situations,

Table 3. Estimated relative values of ecological factors and ZPD for the TEST cohorts (N = 36)

	Fall 2006	**Spring 2007**		**Data sources for inferring relative values**
Factor	**TEST**	**TEST**	**POWERHOUSE**	Classroom ethnographic data, post-experience interviews, private advisor meetings during project, responses to the following survey instruments: Situational Intrinsic Motivation Scale [45], Safoutin Design Survey [44], modified Knowles [43] survey.
Relatedness support	High	Very high	Decreasing to low levels	
Connection to broader context	High	Medium	Decreasing to low levels	
Freedom of choice	Medium	High	Very high	
Zone of Proximal Development	High	High	High	

Table 4. Results of the exploratory factor analysis of the Safoutin Design questionnaire. N = 36

Confidence with open-ended challenges (α = 0.927)		Managing team process (α = 0.887)		Ability to self-regulate (α = 0.858)	
Item #	**Factor Loading**	**Item #**	**Factor Loading**	**Item #**	**Factor Loading**
21	0.823	18	0.916	6	0.764
12	0.816	19	0.825	4	0.735
15	0.756	17	0.807	5	0.658
14	0.744	20	0.650	7	0.639
13	0.611	22	0.543	3	0.636
2	0.607				
1	0.572				
11	0.558				
9	0.526				

so the ZPD trait should be the same for all. The five response choices for this questionnaire asked respondents to rate their ability from Poor to Excellent (Poor = 1) in several competencies embedded in the design process. Exploratory factor analysis of their responses revealed three scales that generally characterize the students self-perception of their (1) Confidence in addressing open-ended challenges (α = 0.927), (2) Ability to manage the team-process (α = 0.887), and (3) The ability to self-direct their learning (α = 0.858). The mean scores for the three scales were (1) 3.82; (2) 3.66; and (3) 3.68 with median scores 3.7 or higher for each of the means. This indicates that half of the students felt their ability was 'very good' to 'excellent.' Although self-assessments are sometimes inaccurate measures of true competencies, we used students' high degree of confidence that they can direct their own learning and address open-ended problems as signs of at a high ZPD. Recall that the ZPD is a conceptual measure of the degree to which students can learn something on their own or with peer-assistance.

3.5 Comparison of simulated and measured trends

In this section, we consider the behavior of the model's simulated trends with a measured construct. We should note that this mathematical version was constructed in 2009, after the learning experiences. This comparison only serves to illustrate the trends the model simulates compared to what was observed, not for the purpose of proving the accuracy of the model, but to show the consistency of the overall trends. We are focused on students' *intrinsic motivation* in the learning situation, as measured using the Situational Intrinsic Motivation Scale (SIMS) [45].

The SIMS is a reliable and valid survey instrument designed to assess four constructs based on self-determination theory*: intrinsic motivation*, *identified regulation*, *external regulation*, and *amotivation* (i.e., feelings of incompetence and uncontrollability). *Identified regulation* reflects a student's value of what is being learned and thus represents motivation based on an internalized goal. For this study, intrinsic motivation (IM) scale was used as the measure of situational intrinsic motivation. We therefore used the *identified regulation* scale in this study as a proxy for the *perceived relevance* flow in the model.

In completing the SIMS, respondents are asked to answer the questions relative to a particular learning situation, so the measures represent situational measures. The SIMS is based on a 16-item, Likert scale (1 = corresponds not at all, to 7 = corresponds exactly). Factor analysis confirmed that the SIMS instrument consisted of four scales that measured intrinsic motivation identified regulation external regulation and amotivation. Internal reliability of these scales was sufficiently high (α>0.78).

Three further instruments were utilized in the Fall 2006 test cohort to validate construct relationships. The first is a self-directed learning scale adopted from an adult learning measure originally developed by Knowles [43]. The 26-item instrument was used to measure students' perceptions of a variety of knowledge, skills, and attitudes related to learning. The survey items represent many of the processes and abilities that are described in the self-regulated learning literature: cognitive (e.g., learning need identification, goal-setting, self-assessment), motivational (e.g., self-concept as an independent learner, initiative, value internalization), behavioral (e.g., time management, resource acquisition), and environmental (e.g., peer collaboration and relating to instructor). Others included the Motivated Strategies for Learning Questionnaire [36] and the Safoutin Design questionnaire [44], to monitor students' confidence in identifying design solutions, as well as team and project management related tasks. These scales were also confirmed through factor analysis and shown to have relatively high internal reliabilities (α > 0.85). Taken together, these scales represent student self-efficacy for open-ended, team-based design challenges. The results of these surveys were used to inform the estimate of the ecological conditions in the learning environment and discern the differences in students ZPD. As a reminder, these surveys were not direct measures of the ZPD, but were used as proxy indicators of whether the students has a 'high' , 'medium' or 'low' ZPD.

Using the relative ecological factors and ZPD

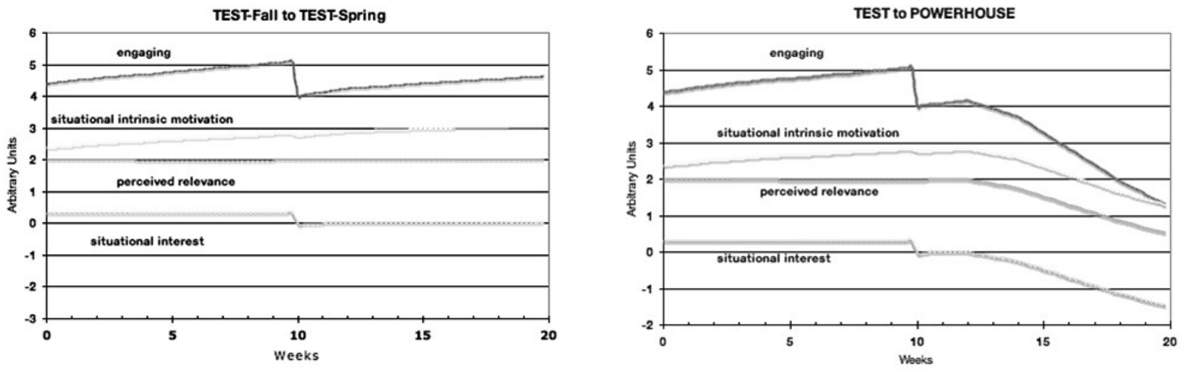

Fig. 8. Model predictions of changes in engaging, situational intrinsic motivation, perceived relevance and situational interest.

values from Table 3, we generated the predictions of changes in engaging, situational intrinsic motivation, situational interest and perceived relevance for the five learning situations. The quasi-cohorts are represented in the single term simulation. One of the important trends shown in Fig. 8 is that engaging varies with the situational constructs, and vice versa. This is not surprising, as learning engagement is known to be respondent to the attributes of and changes within the environment '[46]. The units on the Y-axis are arbitrary.

To examine how the simulations compare to measures, we focus on students' *situational intrinsic motivation.* The simulation output for the three learning situations, along with the measured intrinsic motivation values, are shown in Fig. 9. For these data, the mean IM scores have been scaled by a common factor (0.159) to facilitate comparison. T-tests of the means indicate that all differences in mean values shown in Fig. 9 are statistically significant ($p < 0.05$).

Figure 9 indicates that the model captures fairly well the trends in situational intrinsic motivation for the test group situations (Figs 9a and 9b). For example, in the Powerhouse situation, the model predicts that the situational intrinsic motivation will drop in response to the ecological factors. The SIMS intrinsic motivation measures in the spring are indeed lower than the fall values (2-tailed t-test, $p = 0.038$). The model also simulates that the increased freedom of choice in the spring and higher relatedness would result in a higher IM. The IM for Spring 07 is larger (2-tailed t-test, $p = 0.013$).

4. DISCUSSION—IMPLICATIONS FOR ENGINEERING EDUCATION

One interpretation of these results is that ecological factors play a strong role in students' situational intrinsic motivation. An indicator of this fact is the difference in IM reported by the Powerhouse experience and the TEST-Spring 2007 experience. Recall that these are the same students who indicated their motivation in two different situations. The Powerhouse group also exhibited a higher mean score on the SIMS amotivation scale, a clear measure of their sense of futility in the work. Needless to say, these indicators are not desirable to promote learning. Note that the situation was the main difference, rather than the respondents. This implies that situational or ecological factors are the main actors in causing the students differences in the IM.

Classroom observations of the Powerhouse project interactions support the decreasing trends for engagement and interest predicted by the

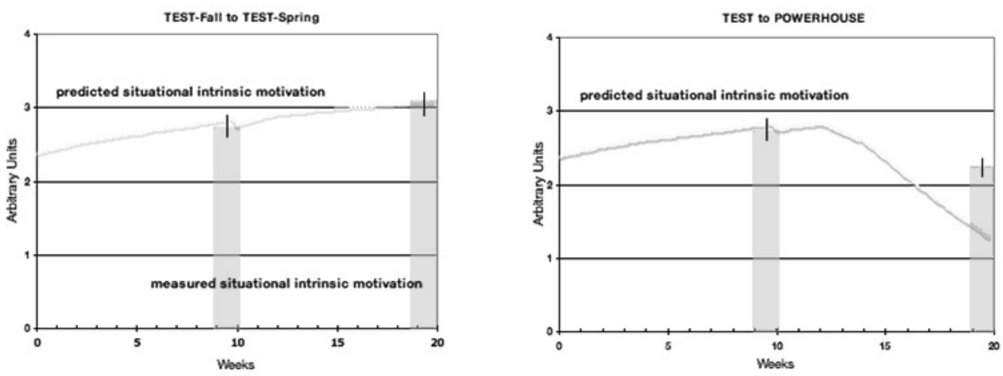

Fig. 9. Comparison of model predictions (curves) and measured situational intrinsic motivation (bars).

simulation (Fig. 8). The post-course interviews confirmed the students' questioning of the relevance of the Powerhouse work to their goals as engineers. Again, the data presented here are not intended to prove the validity of the model, but rather to open up a number of possibilities for the design of effective engineering learning environments.

One of the reasons we examined intrinsic motivation is that it has been shown to play a significant role in promoting a learner's engagement. In theory, more engagement would lead to more learning, a greater appreciation for learning and a greater propensity for adaptive expertise. That is, intrinsic motivation is theoretically a key ingredient for developing the will and skill for a lifetime of learning. For this particular set of learning experiences, we do not have reliable measures of student learning. Although the students reported higher levels of intrinsic motivation and the observed engagement was higher in some learning experiences, depth and breadth of learning were not measured. An important area of future research would be one that establishes the appropriate depth and breadth of engineering knowledge, and that connects the instructor-specified desired outcomes to actual student learning and students' perceived competence.

The findings from this study highlight several important issues that are relevant in engineering course and curriculum design. The first is that the complex interrelationships among different aspects of human development cannot be ignored. Students' thoughts, feelings, and behaviors are all influenced by their past experiences and ecological factors such as the learning goals and constraints, the peer and instructor interactions in the classroom, and the learning climate. Therefore, self-determination and self-regulation theory suggest that holistically addressing these experiences in the classroom can leverage students' total development as learners. The second is that students' perceptions of autonomy, relevance, and value in the learning environment are required for both intrinsic motivation and lifelong learning skill building. While there are many factors at play, meeting students' needs in these areas can fuel the their development of several critical constructs and ultimately their learning achievement. The third is that by gaining a more complete understanding of how students perceive their course experiences, faculty can design learning environments that provide for choice, and adopt instructional practices that support student control, leading to the stronger growth of the *will* and *skill* for learning throughout one's professional life.

Given these findings, we suggest a number of practical approaches to designing learning environments that would lead to greater intrinsic motivation and subsequently greater learning achievement. We recommend the adoption of student-centered teaching modalities such as active and cooperative learning, problem-based learning, project-based learning, and service learning, among others. These pedagogies have at their core the fundamental principle that it is the students who should actively construct knowledge and thus take ownership of their learning. But for these methods to result in intrinsic motivation among students, they must be coupled with explicit attempts to provide students with choice in their learning. Therefore, we suggest that students be more frequently involved in establishing the operating structure of a course including establishment of learning outcomes and even grading schemes. In those courses where problem- or project-based learning is utilized, students should be given the freedom to select problems or projects of personal interest within the practical boundaries of the learning environment and outcomes. Such an approach reinforces both the need for autonomy and relevance. However, students can be given too much autonomy and choice. To avoid this, faculty should carefully coach students in the process of selecting topics and learning goals, frequently check in with students to assess their level of anxiety with a project, and help them to adjust the scope of projects as needed.

Students must also see value in the activities of a course. While this need for value is in part met by allowing student choice, instructors play an important role in helping students internalize the relevance of learning experiences. Instructor interventions aimed at helping students answer the 'Why am I doing this?' are particularly important during critical stages of a project when students feel most overwhelmed by the complexity and uncertainty of the experience. Having external experts visit class and speak to the essential skills students will need to be competent professionals can provide a critical boost to morale. It is also an excellent opportunity for students to demonstrate their competence to an external audience, which can contribute to students' sense of self-efficacy.

Above all, students need to know that it is acceptable to fail within the confines of the classroom. Few individuals could develop true intrinsic motivation in any subject when the external threat of failure is an implied aspect of a course as it is with most courses in engineering education. Even when faculty explicitly attempt to remove this threat through coaching and adjustment of grading schemes, students are understandably wary that somehow the rules of their other classes still apply. Perhaps the faculty members most challenging task will be convincing students that their classroom is indeed a safe place to fail, so long as that failure was part of an honest attempt at self-directed learning.

5. CONCLUSIONS

Engineering education, along with the engineering profession itself, is experiencing a paradigm shift toward a holistic understanding of the dynamic, human systems in which they both are embedded. The authors explore how the use of dynamic simulation can aid the design of learning experiences that support student autonomy, social interactions and perceived relevance—factors that can shift engineering students toward greater intrinsic motivation and engagement in particular learning situations, and toward the long-term development needed for adaptive expertise. We also illustrate how a failure to meet certain psychological needs can provide for low intrinsic motivation and engagement. This exploration is founded on a synthesis of self-determination theory and self-regulated learning research. Our model of the interacting nature of the ecological factors and the learner' psychological needs simulated reasonably well the trends in the changes of the students intrinsic motivation. We present the model as an aid to provide new insights for engineering educators. It allows one to see the opportunity to embed positive ecological factors into the learning environment to enable engineering students to develop traits required for adaptive expertise, such as intrinsic motivation.

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Linda Vanasupa is a professor of materials engineering at the California Polytechnic State University in San Luis Obispo, California. Her recent work is in the area of integrating issues of societal relevance into the engineering design process and design of learning experiences for holistic development. She also serves as co-Director of the Center for Sustainability in Engineering at Cal Poly. She is currently the US-leader for a multi-institutional collaboration with Tongji University (Shanghai, China) on innovation and design of sustainable communities for the rural Chinese.

Jonathan Stolk is an associate professor of mechanical engineering and materials science at Franklin W. Olin College of Engineering. His recent work includes examining the role of faculty in promoting students' growth as self-directed learners, exploring the effects of disciplinary integration and project-based learning on students' motivation and competency development, and applying design thinking to engineering curriculum reform.

Trevor Harding, Ph.D., is associate professor of materials engineering at California Polytechnic State University, where he teaches courses in materials engineering design. His research is focused on understanding the process of ethical decision-making in engineering and how this process develops over time, particularly in the college years. He is currently PI on a multi-university collaborative research study assessing the ethical outcomes associated with the curricular and extra-curricular experiences of engineering undergraduates. Dr. Harding serves as Associate Editor of the on-line journal Advances in Engineering Education, is program chair for both the Materials and Educational Research and Methods divisions of ASEE.