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Exploring Student Differences in Formulating Cross-Disciplinary Sustainability Problems*

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Every day engineers are confronted with complex grand challenges. Grand challenges related to natural disasters represent a class of complex problems that require working across multiple disciplines and involve not just solving the immediate problem but designing long-term sustainable systems. In this paper, we present exploratory work to characterize students' ability to formulate cross-disciplinary problems for a complex, contextualized, and cross-disciplinary disaster relief scenario. This includes a description of the study implemented in three global contexts, data collection, analysis, and results including a discussion of the utility of the scenario tool to distinguish group differences. The paper concludes with implications for research, instruction, and assessment.

Keywords: design; cross-disciplinarity; sustainability; problem formulation

1. INTRODUCTION

ENGINEERING IS inherently cross-disciplinary—integrating broad knowledge towards some purpose lies at the core of the engineering profession [1]. Here, 'cross-disciplinary' is used to present a collection of practices (e.g., multidisciplinary, interdisciplinary, and transdisciplinary) that signify variations in the ways individuals create, collaborate, and communicate across differences in training or lived experiences [2–3]. Many studies confirm how the nature of engineering work involves thinking and working across technical and non-technical considerations (e.g., human, social, economic, political), negotiating among different perspectives and territories of expertise [4–5], transforming knowledge through reflective practice [6], analogical reasoning across multiple perspectives [7], and managing trade-offs where solutions are judged by interdisciplinary criteria [8]. Through cross-disciplinary practice people come to understand new ways of innovating and combine different perspectives in novel ways [9]. As we move into a global future, the ability for engineers to work in cross-disciplinary environments will be an essential competency to address the issues of a 'Flat World' [10].

Every day engineers are confronted with complex cross-disciplinary grand challenges ranging from natural disasters to developing novel solutions to improve the quality of every day life. The National Academy of Engineering published a list of 'grand challenges' that speak to the every day needs of people and the planet regarding access to clean water, health systems, shelter within an urban infrastructure, and sustainable energy [11]. From a systems perspective, a key issue to consider in these cross-disciplinary problems is a goal of sustainability.

Sustainable design focuses on seeing the whole system—goals and potential effects, immediate and wide-ranging, with respect to time and place. Harding [12] notes that sustainability should be the framework through which all engineering activity must take place because scientific and technical aspects of engineering operate within a broader social, environmental, political, and global context. To be effective in the future, sustainability practices must not only span all the traditional disciplines, but also transcend traditional boundaries by working together alongside other fields including architecture, science, social science, philosophy, business and political science [13].

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Identifying and formulating complex, contextualized, and cross-disciplinary problems plays an important role in how we prepare engineers for professional life [6, 14–15]. It is also important for how we prepare future engineers to address global needs and collaborate across diverse perspectives and cultures [11, 16]. Reports on the future of engineering education emphasize the importance of preparing engineers to become professionals who can deal with complexity, innovate, flexibly adapt to new situations, and bridge disciplines to produce deeper insights [17–19]. This focus on problem formulation aligns with current views on sustainability. Cradle-to-cradle approaches are inherently problem-focused in that they focus on working on the 'right things' rather than trying to make the 'wrong things' less bad [20].

Many efforts in improving engineering education seek to provide rich opportunities for engineering learners to develop skills in formulating and solving complex, contextualized, and cross-disciplinary problems that address sustainability issues. This is evident in the growth of cross-disciplinary (1) programs (e.g., ranging from service learning programs and *Engineering without Borders* [21] to new cross-disciplinary undergraduate degrees such as ecological engineering), (2) curricula (e.g., seminars and short courses, and senior capstone experiences), and (3) research and design collaborations. These efforts span undergraduate and graduate education. For example, the *Institute without Boundaries* [22] is a center for graduate research and learning focused on effecting positive change for humanity. One of their projects, World House, seeks to confront the evolution of shelters for coming generations for incorporating principles of sustainability, accessibility, technological responsiveness, and ecological balance.

There is considerable need to understand the ways such programs prepare engineers to become future global design professionals. As part of an effort to design and implement a cross-disciplinary engineering undergraduate degree, we developed a tool to investigate the impact of this program on students' abilities to formulate complex, contextualized, and cross-disciplinary problems. Students were given a 'disaster response system' scenario and asked to identify the issues they consider important and the expertise they would want on their team and why. As an exploratory study, our broad research questions include: (1) *how can we effectively characterize problem formulation abilities for this scenario type?* and (2) *what is the utility of this approach in revealing relevant group differences?*

The scenario task was implemented in three global settings: two in the United Stated and the third in China. Settings differed in the extent to which (1) a natural disaster had recently been experienced in that area and (2) students had received guided instruction on cross-disciplinary engineering or sustainability perspectives. For example, the tool was implemented in a multidisciplinary professional seminar in an academic setting where tornadoes are a likely natural disaster yet one had not occurred in the specific area for more than five years (N=12), at a site in New Orleans where students involved in a service-learning project were working as part of a project related to Hurricane Katrina (N=12) [23], and an academic setting in Beijing less than one month after a significant earthquake (8.0 on the Richter scale) was experienced in Sichuan (N=24). These differences created opportunities to explore how the scenario tool may distinguish group differences.

2. BACKGROUND

This section summarizes empirical research on problem formulation in design and describes the three lenses that guided the study—cross-disciplinarity, systems thinking, and sustainability.

2.1 Problem formulation in design

Empirical research consistently illustrates the importance of problem formulation abilities in engineering design. Studies have shown significant correlations between problem formulation activities and design success and expertise [15], reflective practice [6], adaptive expertise [24–25], and more holistic approaches to sustainable design [26]. For example, in a study comparing engineering freshmen and seniors designing a fictitious playground, seniors gathered more information about the problem across more categories such as budget, safety, maintenance, materials, and labor [27–28]; a similar trend emerged from a study on the information gathering activities of practicing engineering experts [29]. For both studies, information gathering behaviors significantly and positively correlated with final solution quality.

Many studies of problem formulation abilities illustrate the utility of providing a design scenario, asking individuals to list the issues they consider important, and then analyzing the types of issues listed. In a series of studies investigating the breadth and depth of issues considered important for designing a flood retaining wall for an area in the Midwest, statistical differences were observed across gender [30] and within groups over a four-year engineering curriculum [14]. The coding scheme supported analysis across types of knowledge considered (technical, logistic, social, environment) in relation to the physical frame of reference (the wall, the water that interacts with the wall, the shoreline, and the community) [see 31]. This coding scheme was also translated for a discipline-specific scenario for industrial engineering students [32].

2.2 Cross-disciplinary systems thinking

For this paper, the term *cross-disciplinary* represents a collection of practices associated with thinking and working across different perspectives: multidisciplinary, interdisciplinary, and transdisciplinary. Where disciplinary practice may be signified as a deepening along a vertical axis, cross-disciplinary practice is often signified as a horizontal axis of breadth, comprehensiveness, and synthesis [33]. This is often represented as a 'T', and those who work cross-disciplinarily are often referred to as 'T people' or complex systems thinkers. Systems thinking approaches, including communication, collaboration, and attuning to the human aspect of engineering problems have been shown to be important features of cross-disciplinary practice in engineering contexts [3].

Nelson and Stolterman [34] define systems thinking as seeing and seeking interrelationships, encouraging emergent phenomenon, and thinking in terms of wholes rather than parts. They describe systems thinking as the logic of design—assemblies of interrelated functional relationships between the *design context* and *design intentions*. Design intentions represent the process of giving direction to 'that which is desired', provide a framework for framing and judging design decisions, and emphasize the importance of problem formulation in design. The design context embodies aspects of interacting systems (e.g., technical, social, political and economic perspectives) and their related functions. Nelson and Stolterman illustrate the relationship between design context and intentions through 'system palette' representations [34]. These can be two-dimensional representations that parallel other coding frameworks [14, 31] yet differ in their ability to characterize how an intention or goal may be achieved through a mix of cross-disciplinary inquiry within a contextualized system frame.

2.3 Sustainable design

McLennan [20] defines sustainable design as a philosophy that seeks to maximize the quality of the built environment by regenerating environmental and social systems while minimizing or eliminating negative impact to the natural environment. This emphasizes a philosophy of doing more with less, generating less waste and pollution, using renewable rather than non-renewable resources, minimizing the harmful affects on human health and the environment, and working on the 'right' things rather than trying to make the 'wrong' ones less 'bad' [20, 35]. This expands the scope under consideration from the primary purpose of a product or system to consider the whole—what its goals and potential effects are, both immediate and wide-ranging, with respect to both time and place [26]. This view of sustainable design emphasizes the need for cross-disciplinary teams and systems thinking that links resources, infrastructures, people, and society.

A recent empirical investigation provides further support for the relationship between problem formulation and sustainable design [26]. Twenty-two practitioners (practicing engineers and other professionals many of whom worked across multiple disciplines) were interviewed about their experiences with sustainable design and the resulting transcripts were analysed using a phenomenographical approach. The results show that more comprehensive experiences of sustainable design emphasize the importance of problem formulation and systems thinking with a particular emphasis on a life cycle of complex impacts to social, environmental, and socio-technical systems. The outcome of the study is a framework of five categories each representing a qualitatively different way of experiencing sustainable design: solution finding, reductionist problem solving, holistic problem solving, social network problem, and a way of life. These categories go from least comprehensive to more comprehensive in their inclusion of aspects related to time available, scope of work, and flexibility.

3. METHODS

The focus of this study was to design and implement a tool to investigate students' abilities to formulate complex, contextualized, and cross-disciplinary problems involving sustainability issues. The following sections describe the design task, the study participants, and the process of collecting, coding, and analyzing the data.

3.1 Design task

The frameworks presented in the Background section guided choices regarding the nature of the task scenario and ways to elicit problem formulation knowledge. As shown in Fig. 1, the participants were given a scenario and asked to identify: the issues they would consider important and the expertise they would need (team members). Characteristics of the scenario exhibit features of authentic design tasks [36–37] including: ambiguity, the existence of multiple possible solutions, complexity and interrelated functions, authentic stakeholders, and cross-disciplinary needs that link technical, environmental, social, economic, and political perspectives. Sustainability was integrated into the scenario by focusing on regenerating environmental and social systems [20], interrelationships between time and scope of work [26], and the ways potential effects may be immediate and far reaching across societal, economic, technological, and environmental dimensions [12].

As noted earlier, elicitation methods were selected based on existing research on problem formulation that illustrates the utility of asking participants to list the issues they consider important for a particular situation. The question on what kinds of expertise would be needed was added to specifically elicit cross-disciplinary perspectives. This fits with a complex system design framework that encourages a mix of disciplinary inquiry within a system frame [34] and a

DISASTER RELIEF SCENARIO TASK

Directions: Consider the following scenario – and respond to the questions below. This activity will take 30 minutes. Please be honest in your response. This is not a "test" - there are no right or wrong answers to these questions.

Recent Natural disasters (e.g., tsunamis, earthquakes, hurricanes, tornadoes, fires, and floods) were a hot topic at the International Conference on Predicting and Responding to Natural Disasters last month. The conference brought in people with diverse backgrounds from around the world, particularly those who live or work in "disaster-plagued" areas such as Florida and Singapore. At the end of the conference, you (as an Multidisciplinary Engineer) were asked to bring together a team that would focus on developing new ideas for a "disaster response system" for tornadoes in Tippecanoe County.

- What issues do you think are important to consider? Please use the back of this page if you need more space.
- Who would you want on your team? For each team member identify the expertise they would bring and how (or when) they would contribute to the project.

Fig. 1. Disaster relief scenario task.

sustainable design framework that emphasizes a network of expertise [26]. Triangulating responses between the *expertise* and *issue* questions provides opportunities to analyze relationships between issues considered important and the kinds of expertise necessary to address these issues.

3.2 Participants

The task was implemented in three global settings to examine the ways in which the task may reveal relevant group differences as shown in Table 1. Two settings were in the United States (Midwest and the Southeast) and the third was in a metropolitan area in China. All participants were enrolled in a post-secondary institution and pursuing at least a baccalaureate degree. Characteristics across study cohorts are summarized in Table 1.

Each cohort differed to the extent that they lived or worked in an area that recently experienced a natural disaster such as a tornado, hurricane, or earthquake. This allowed exploring how proximity (time and space) and experience (personal and educational) may influence the ways students formulate complex, contextualized, and cross-disciplinary problems. For example, the China participants, who resided in Beijing, were closest in time to a major natural disaster (the Sichuan Earthquake of 2008 that measured 8.0 on the Richter scale). Three elements made the disaster relevant for the Chinese students: people in Beijing high-rise buildings reported feeling their building sway at the time of the earthquake, reports on the ground response came almost immediately and was extensively covered with live media footage, and a number of the China participants commented to the task administrator that they had friends of family that were directly impacted by the earthquake.

In contrast, the US (Katrina) group was closest in space to a major natural disaster (Hurricane Katrina of 2005). This group of students worked for three months, on a daily basis, rebuilding homes at 'Ground Zero' for Hurricane Katrina: the cities of Bay St. Louis and Waveland, Mississippi [23]. These students had daily exposure to hurricane victims, ongoing recovery efforts, and the complex (economic, social, cultural, emotional) impacts of Katrina on individual residents and larger groups (local governments, faith-based organizations, community relief groups, etc.). Finally, the US (MDE) group was most removed in time and space from a natural disaster (the last tornado in the county occurred before their enrollment at the school) but may have had the closest personal relationship to the natural disaster type due to the frequency of tornado warnings during a typical school year.

Cohorts also differed in their academic training and whether they were recruited from an environment that included instruction on issues pertinent to the task (e.g., complex systems, cross-disciplinarity, sustainability). The US students were

Table 1 Group characteristics of study participants.

	US (MDE)	US (Katrina)	China (Engineers)	China (Non-Engineers)
TOTAL	12	12 (4 teams of 3)	11	14
Proximity—Time	Historical > 5 years	Recent (1 year)	Recent (1 month)	Recent (1 month)
Proximity—Location	On-site, no recent impact	On-site, after impact	During impact	During impact
Natural disaster type	Tornado	Hurricane	Earthquake	Earthquake
Guided instruction	MDE Professional Seminar	Service-learning immersion	n/a	n/a
Engineering majors	Yes	Mix with social science, law, etc.	Yes	No

recruited from specific educational programs while the Chinese students were recruited from university dining and study halls used by engineering and non-engineering majors. More specifically, the US (MDE) students were enrolled in a Multidisciplinary Engineering (MDE) major at a major Midwest university. The program included an integrated science class, engineering content courses using cross-disciplinary pedagogies such as collaborative teaching, and multiple cross-disciplinary design experiences such as service learning experiences and a capstone design course. Study participants were recruited during a sophomore/junior professional seminar designed to complement their other courses. The goals of this one-credit seminar were to help students identify contemporary issues that drive a need for cross-disciplinary approaches, develop a professional identity as a cross-disciplinary engineer, and understand the kinds of knowledge and skills necessary to be a successful cross-disciplinary engineer. Students discussed readings [e.g., 9], engaged in a variety of activities such as finding contemporary cross-disciplinary problem and defining the kinds of issues or knowledge they involve, and produced a cross-disciplinary elevator speech and plan of study for their remaining coursework.

In comparison, the US (Katrina) students were in an undergraduate program at a major Northwestern university and were pursuing a variety of majors ranging from engineering to law and social justice [23]. The students were recruited during an innovative integrated and immersion service-learning experience in a domestic study abroad experience that drew heavily on active, collaborative, and experiential learning components of the Community of Learners model by Brown and Campione [38]. The curriculum integrated formal academic coursework (a 5 credit course 'The Impact of Katrina on Technology and Infrastructure' and a 1 credit service-learning seminar) simultaneously with immersion in service and an intensive application of technology and engineering concepts in a timely situation of national relevance. All of this occurred on site during the second year of a 15–20 year recovery effort in city of Bay St. Louis where Hurricane Katrina had the most devastating impact. The service-learning component involved 3.5 days per week over a 10-week term, rebuild assignments (e.g., from gutting to sheet rock installation and plumbing), and local outreach to a displaced elementary school (e.g., supporting Katrina-related science fair projects such as hurricane proof home construction and wetlands storm surge protection). Immersion allowed delving into unanticipated issues such as the impact of a former hurricane (Hurricane Betsy) on the toxicity of a landfill site occupied primarily by disenfranchised people in New Orleans as well as forming longer-term relationships with those affected in the community. The academic component addressed critical analyses of natural disaster leadership, response, and recovery through weekly reflections on readings, a term paper, and an electronic portfolio.

3.3 Data collection

All participants were given the same amount of time to complete the task. Data was collected over a two-year period starting first with the US (MDE), then the US (Katrina) group, and then the China groups. The US (MDE) participants completed the task on the last day of the MDE Professional Seminar, the US (Katrina) participants during the last week of their guided service-learning experience, and the China participants within a month of the Sichuan earthquake. For the Chinese participants, study materials were translated into Chinese and the task was modified from a tornado scenario to an earthquake scenario. All Chinese participants had the opportunity to write responses to the task in their language of choice, which was then translated into English for data analysis.

3.4 Coding the data—sustainability intentions and cross-disciplinary functions

All identifiers were removed and the data was placed in an excel database. While existing research suggests frameworks for characterizing problem formulation abilities, they are limited in their ability to address cross-disciplinary systems thinking or sustainability perspectives. Therefore, we developed alternative coding schemes following a grounded theory approach [39]. The coding process began with segmenting the data from each question into distinct units or ideas, printing these onto separate pieces of paper that included a student identifier, and sorting the papers into piles. This was an iterative and collaborative process that continued until a consistent and reliable set of interrelated categories emerged.

The first coding scheme, the Intention codes, characterize a sustainable systems perspective as a time-sensitive, goal-directed cyclic process of minimizing impact on the system, maximizing speed of recovery, and enhancing the environment by designing for sustainability. Individual categories and their relationships are summarized in Fig. 2. As shown here, the codes characterize phases (in time, scope of work, and flexibility of resources) of a disaster relief plan: prevention, first response, treatment, up and running, recovery, and design for future improvements. *Prevention* characterizes efforts to minimize the level of damage once a disaster occurs (e.g., meteorology efforts, early warning systems, safety standards, resource reserves, understanding how tornadoes work); *First Response* refers to efforts to minimize the speed of response once a disaster occurs such as practice drills and training sessions. *Treatment* characterizes efforts to treat and manage the impact of the disaster to people, places, structures, and infrastructures. One goal of a disaster relief plan would be to minimize the duration of the treatment phase so that the system could quickly

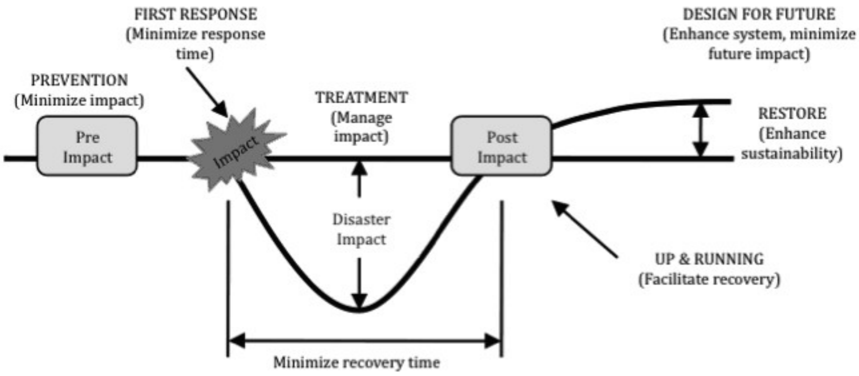

Fig. 2. Intention coding scheme for disaster relief scenario.

get *Up and Running* for long-term recovery (e.g., ways to get the community back on track including business and financial planning). *Restore* characterizes efforts to move the system towards sustainability across social, economic, political, and environmental needs; in other words reconstructing the system to where it could maintain itself without considerable external resources. Finally, *Designing for Future Improvements* is a phase that re-enters the prevention phase by focusing on sustainable design through new and safer structures, infrastructures, standards, or processes that would minimize the impact of a future disaster or maximize enhancement of the disaster zone. We also coded for process activities including creating the actual disaster relief plan, making choices about who would be on the team, and evaluating the final plan. These were categories of a Planning coding scheme that focus on the social and management dynamics within a cross-disciplinary team.

To characterize cross-disciplinary systems perspectives we added a second layer to the coding scheme, Function codes. These characterize the cross-disciplinary functional aspects of the system: Resources, Infrastructure, Humanist, Communication, Management of plan development, and Management of the plan in action. These are typical categories for describing complex techno-social systems [34]. A description of these categories is provided in Table 2. Investigating interactions between the Intention and Function coding schemes allowed analyzing how a particular goal such as Treatment related to particular functions such as humanist or communication functions. It also allowed analyzing how a person with a particular expertise (from the 'expertise' question) might be needed for various system goals as characterized by the Intention codes (from the 'issues' question).

4. RESULTS

Research questions guiding this exploratory study include: (1) *how can we effectively characterize problem formulation abilities for this scenario type?* and (2) *what is the utility of this approach in revealing relevant group differences?* A statistical average was calculated to facilitate across group

Table 2. Function coding scheme.

Functional categories	Descriptions
Resources	Financial: Provide finances to aid response to a disaster. Physical: Meet basic physical needs. People: Labor (skilled, unskilled, professional) to do whatever is needed.
Infrastructure	Clean-up: Help clean area. Rebuild: Help rebuild/restore area. Improve: Improve the structure to decrease future damage. Inspect: In order to ensure safety of users.
Humanist	Medical: Heal the injured. Emergency Services (non-medical): Search and rescue, population control and management. Counseling: Manage distress and displacement, focus on quality of life.
Communication	Historical wisdom: Provide information on past experiences. Ease: Facilitate understanding between people, get social system back on track. Warning: Provide a clear and reliable warning to people.
Management (create plan)	Evaluate: Assess likelihood of plan working. Team choice: Determine expertise needed to create response plan. Plan: Creating a plan for future disasters.
Management (plan in action)	Evaluating: Monitor how the plan worked or if changes are needed. Team choosing: Determine expertise in current response effort. Planning: Response is made as planned.

comparisons. The unit of analysis was based on individual participant responses except for the US (Katrina) group, which completed the task as groups of three. A full statistical analysis was not conducted due to the limitations of the study; rather, the focus is on illustrating and exploring trends in responses to the scenario that may guide future work. Findings are summarized in the following sections through three lenses (1) sustainability as an intentional goal, (2) planning goals, (3) cross-disciplinary functional requirements, and (4) system interactions between intentions and functional requirements.

4.1 Sustainability as an intentional goal

As stated earlier, the Intention codes provide a way to characterize abilities to formulate complex design problems through a sustainability lens. This coding scheme emphasizes issues of time, scope, and flexibility regarding full recovery of a social, human, technical, economic, and political system (Fig. 2). As shown in Fig. 3, intentions emphasized Treatment significantly above all other issues. Issues coded as Treatment, similar to those coded as First Response, involved addressing short-term needs of specific scope and limited flexibility in time-sensitive response actions. Treatment issues spanned a variety of human, infrastructure, and system needs: search and rescue, food and shelter, clean water, medical and counseling, utilities, transportation routes, communication networks, security, and government declarations of emergency. One explanation for the emphasis on Treatment may be the typical level of media coverage on disasters, the visceral quality of watching the impact of disasters on human life, or the immediacy of life and death human needs. As one student in the China group notes, 'the lives of the people are most important.' The kinds of expertise participants associated with Treatment issues included leadership roles such as a town mayor as well as specific training such as emergency workers, medical personnel, psychiatrists, police and firemen, and a variety of engineers (e.g., chemical, civil, construction).

There were unique responses across groups regarding Treatment. Only the China participants identified issues of microorganism and disease control, media coverage, and after shocks (an issue perhaps unique to earthquakes). Disinfection was one of the highest priorities mentioned by China's President and spraying disinfectant was a constant image in the media coverage of treatment efforts. For example, one Chinese participant was concerned about the likelihood of 'potential secondary disasters, earthquakes for instance have aftershocks that bring a lot of people troubles, and predicting probable future disasters is important.' China participants were also unique in identifying traffic management and control issues, which may be indicative of life in urban 'megacities'.

The US (Katrina) participants were unique in identifying a need to declare a federal or state emergency as necessary for releasing funds for large scale relief and recovery efforts. One explanation may be that these students were heavily exposed to residents who were still talking about the impact of Katrina, in particular their experiences with the shock of a massive loss of infrastructure and their anxieties in continuing to meet daily human needs. The US (Katrina) participants were also unique in their ability to identify local expertise to meet Treatment issues such as equipping local Wal-Mart managers with quick access to resources and people who 'control shelter areas'. This may be a form of insider knowledge unique to their on-site experience.

Students were far less likely to cite Prevention issues for the disaster relief scenario, particularly the US (Katrina) participants. Prevention issues included warning systems, effective means for predicting and communicating impending peril, evacuation plan development, and safety education. Prevention considerations, similar to Design for Future issues, focused on long-term needs of broad scope and time span, enabling greater flexibility in future response actions. Expertise associated with Prevention issues included meteorologist and geologists, people with historical wisdom in the area (e.g., police, firemen, emergency workers), communication specialists,

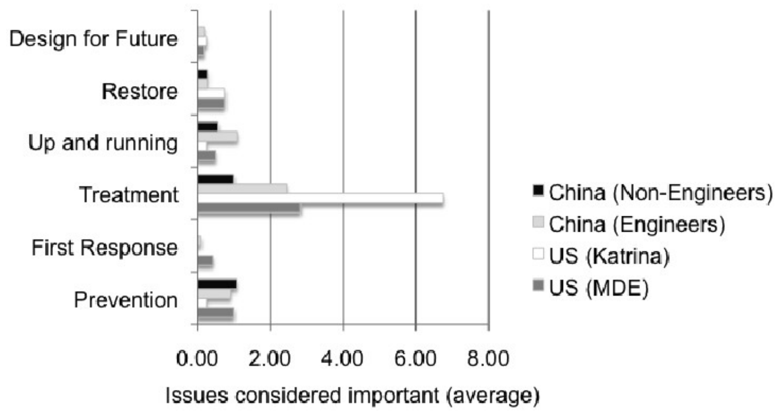

Fig. 3. Intention coding scheme analysis across groups for issues considered important.

and architects and engineers who can retrofit or rebuild physical structures.

The US (Katrina) participants may have been less likely to identify Prevention issues or expertise because they were immersed in ongoing community-based restoration efforts and dealing with a substantial lack of crucial infrastructure to move beyond treatment efforts. When they did identify Prevention issues they were unique in identifying 'fund reserves to aid people at all levels of government' and lawyers who could manage or accelerate insurance claims. Their deep immersion in recovery efforts may have focused their awareness on the long-term impacts of inadequate treatment efforts and hence their greater focus on Treatment issues [23]. For example, some of the US (Katrina) participants were involved on a toxic landfill project that was the result of a prior hurricane (Hurricane Betsy). Proximity to a disaster also appeared to influence the China participants' responses. Prevention issues emphasized a need for better warning systems and safety education: '(t)he earthquake that happened in Sichuan caused much more damage because it was unprecedented', 'make knowledge of self-protection principles universal', and 'organize information into brochures, putting them into things such as strip cartoons, for adults, to spread more easily.' They also emphasized a need to improve pre-existing conditions to reduce the spread of disease should a disaster occur.

As a group the US participants, as compared to the China participants, were less likely to identify post-disaster Up and Running issues such as clearing up roadways and traffic, establishing consistent water and food supplies, power and communication grids, and resettling victims. A consistent unique feature of the China responses was a focus on controlling the spread of disease which one student relates 'to the national status of being a developing country' and a related need for 'help from other countries'. Further, the China (Non-Engineers) participants were more likely to focus on social and medical issues, rather than physical infrastructure issues, as part of getting the system back on track: 'a person who can provide us medical treatment. His work starts before we arrive at the area. He must keep us healthy and energetic for work.' This trend may be indicative of differences in academic training as well as cultural differences [40]. In comparison, the US (Katrina) participants were more likely to focus on engaging and drawing upon resources in the local community such as calling 'a town meeting and find out what people can do' and finding 'local contractors.' Again, just as their on-site immersion may have influenced the kinds of expertise they identified as necessary for treating disaster response issues, their localized experience may have prompted a belief that Up and Running issues were the responsibility of government officials and as such outside their sphere of influence.

Restore and Design for Future issues were also less evident in participants' responses; however, Restore issues were particularly salient for the China and US (Katrina) participants. For example, one US (Katrina) participant listed 'homes and businesses will be gone and it is important to get them back to normal quickly' and a China (Engineer) participant listed 'the most important issue is to help the affected people to escape the disaster's shadow as soon as possible, including recovering local economy.' There were also differences across the kinds of expertise identified. US (Katrina) participants identified local expertise such as 'DIY (do-it-yourself) folks' while US (MDE) and China (Engineers) participants identified broad expertise such as different kinds of engineers, construction workers, architects, legislators and politicians, environmental and ecological scientists, and even entrepreneurs who 'understand the financial aspects of a large-scale project' and are 'willing to try new ideas'. Again, the US (Katrina) participants had on-site experience with the complete collapse of the urban infrastructure which may have prompted a reliance on local over external expertise. Consistent with a focus on more human and social issues, the China (Non-Engineers) participants identified a need for various kinds of social science specialists. Finally, few participants identified Design for Future issues and those who did focused on disaster resistant housing. As an interesting note, some US (MDE) students identified a need for mathematicians who could do extensive analysis on the probability of structural damage in the future.

4.2 Planning

Table 3 summarizes average response patterns across the two task questions for each coding scheme (expertise responses are in parentheses). In most situations, results across task questions were complementary—participants who identified particular kinds of issues were also likely to identify related expertise needs. For example, a participant who identified a need for meteorological data often identified a need for meteorologists on the design team; participants who identified a need for search and rescue expertise often identified a need for finding and treating trapped disaster victims. There were few instances where a particular kind of expertise such as a medical nurse was associated with multiple Intention goals. For example, one China participant identified general medical knowledge as being broadly applicable across many sustainability goals such as planning the plan, emergency response during treatment, disease management to get a system up and running, and restoring infrastructure for clean water and sanitation.

While most responses to the two task questions were complementary there was one exception. The results in Fig. 4 illustrate across group differences for the Planning code for both disaster relief questions. China participants were more likely to identify planning issues in response to the question

Table 3. Group averages for all coding scheme categories for both task questions (expertise and issues)

	US (MDE)	US (Katrina)	China (Engineers)	China (Non-Engineers)
Unit of Analysis	Individual	Teams of 3	Individual	Individual
Intention: Issues (Expertise)				
TOTAL	*11.5 (9.25)*	*4.88 (3.25)*	*8.00 (7.38)*	*6.25 (8.12)*
Prevent	1.00 (1.75)	0.25 (0.75)	0.91 (0.45)	1.07 (1.00)
First Response	0.42 (0.50)	0 (0)	0.09 (0)	0 (0.07)
Treatment	2.83 (2.67)	6.75 (4.00)	2.45 (2.54)	1.00 (0.71)
Up and Running	0.50 (0.33)	0.25 (1.25)	1.09 (0.45)	0.57 (0.36)
Restore	0.75 (0.58)	0.75 (0.50)	0.27 (0.55)	0.28 (1.07)
Design for Future	0.17 (0.17)	0.25 (0)	0.18 (0)	0 (0)
Planning: Issues (Expertise)	2.00 (0.17)	1.50 (0)	0.82 (1.36)	0.64 (1.78)
function: Issues (Expertise)				
Resources	1.17 (0.92)	3.00 (2.25)	1.00 (0.45)	0.71 (0.86)
Infrastructure	1.67 (1.92)	0.50 (1.00)	1.36 (1.00)	0.36 (0.79)
Humanist	0.83 (1.25)	2.00 (1.25)	1.00 (1.55)	0.50 (0.64)
Communication	1.50 (1.33)	2.50 (1.00)	1.00 (1.09)	1.14 (1.71)
Management (create plan)	1.42 (0.08)	0.50 (0)	0.55 (0.55)	0.14 (0.50)
Management (plan in action)	1.00 (0.67)	1.25 (1.00)	0.91 (0.73)	0.57 (0.14)

about what expertise was necessary for the team, whereas the US groups were more likely to identify these in response to the question about what issues are important. This result may reflect the emphasis on content (issues) over explicit teamwork based instruction that is prevalent in US engineering instruction. It also suggests that responses to both questions may be necessary to fully characterize participants' understanding of the task. Finally, while it is valuable that participants identified planning issues, the low averages for this code across all groups illustrate how challenging it may be for students to identify these kinds of broad impacts given their under-representation or superficial role in typical engineering curricula [41].

4.3 Cross-disciplinary functional requirements

The Function codes represent systems knowledge across diverse socio-technical system components that acknowledge management and planning needs. As shown in Fig. 5, the US (Katrina) and China (Non-Engineers) groups have similar patterns that emphasize resource, communication, and humanist issues. They may be similar due to their shared experiences around significant disasters or to their group composition as predominantly non-engineering majors. Examples of communication issues include having information systems with open communication channels, helping people get connected, local historians or guides who have knowledge of past disasters, and weather people who can provide information for media networks. Humanist issues focused on addressing people's needs and maintaining the peace; the associated expertise needed to meet these needs include rescue workers, medical and psychiatric specialists, local law officials, and pastors. Resource issues ranged from skilled or volunteer labor to insurance or fund reserves to survival supplies and shelter to agreements between utility companies and the local or national government.

The US (MDE) and China (Engineers) groups have similar patterns that emphasize infrastructure and management issues, which may be due to their shared engineering training. Examples of infrastructure issues include building and repairing structures, restoring ecosystems and cleaning up hazardous waste, transportation and communication systems, and disease control. Associated expertise included structural and civil engineers, construction workers, environmentalists, ecologists, and traffic engineers. Issues regarding the creation of the disaster relief plan include organization and leadership, ways to mobilize groups, maintenance and flexibility of the plan, and transparency of information. Issues regarding managing the plan in action included mediating team dynamics and evaluating progress to plan. Comparing results across the Intention and Function coding schemes it becomes evident that although the two China groups appear similar for the Intention analysis, they differ significantly for the Function analysis. This suggests that each coding scheme brings a unique contribution to understanding how participants formulated this design problem.

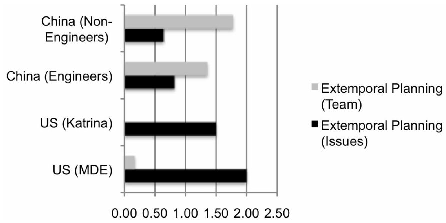

Fig. 4. Planning code average across groups.

4.4 A systems view—relating sustainability intentions to functional requirements

Combining the Intention and Function coding schemes into a 'system palette' [34] provides an integrated analysis across all problem formulation lenses. These are provided in Figs 6a–d as a *group average*. These system palettes illustrate the

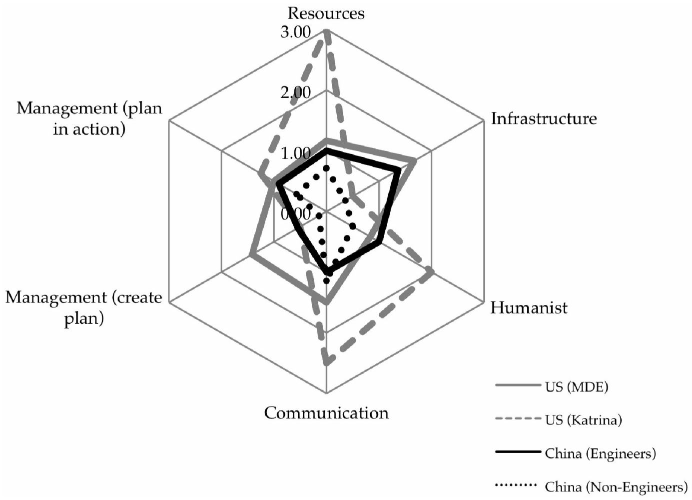

Fig. 5. Function analysis across all groups for issues considered important.

breadth and depth of issues considered as well as opportunities for improvement. In these diagrams, breadth is represented as the number and location of squares across multiple Intention-Function intersections (e.g., the intersection of Treatment goals and humanist functions). Multiple squares across the grid illustrate the extent to which the system palette is broadly defined. Depth is represented as the extent to which the squares are 'filled'. For example, '□' represents a group average of less than 0.25 responses, '▣' a group average between 0.5 and 0.75 responses, and '■' a group average between 1.5 and 2.0 responses. As such, the type of square is indicative of the depth of understanding associated with a particular intersection in the diagram.

A number of system patterns can be discerned by using the US (Katrina) group as a reference point. On average the US (Katrina) group had depth and breadth of Treatment goals across multiple functional requirements—resources, humanist, communication, and management (Fig. 6a). Here, breadth is evident in the diversity of functions considered important for disaster treatment and depth is evident in the number of issues identified for each functional requirement (i.e., the extent to which the square is a solid fill). Humanist functions were the most common issues; however these were identified only in relation to Treatment goals. The US (Katrina) participants also tended to identify resource needs across multiple goals (e.g., Treatment, Up and Running, Restore, and Planning) as compared to infrastructure needs. The pattern in Fig. 6a also illustrates a clear emphasis on post-disaster issues such as Treatment, Restore, and Design for Future issues. The US (Katrina) students were immersed in day to day issues and may have found it difficult to switch gears into a broader vision across time scales; however the term papers they submitted at the end of the immersion experience reflect an awareness of pre-disaster Prevention issues [23].

While the US (MDE) group had a similar pattern regarding breadth or coverage of post-disaster treatment issues across multiple functional requirements (Fig. 6b), there were some notable differences that may be associated with their engineering training or experience with disaster warning systems. First, on average there was more breadth of responses for Prevention (e.g., infrastructure and communication) and First Response goals (e.g., infrastructure, humanist, communication, and management in action). Second, where the US (Katrina) group emphasized resource needs across multiple goals the US (MDE) group emphasized infrastructure needs across goals of Prevention, Up and Running, and Restore. This may be an influence of their engineering training. The engineering students were a minority in the US (Katrina) group—only three of the twelve were in an engineering major. Finally, while the US (Katrina) group had greater depth of responses, the US (MDE) group had greater breadth. This may be an influence of course activities in the MDE program that focused on helping students think broadly. What the US (MDE) students may have lacked is depth of understanding around these broad issues that may be developed through an extensive immersion experience.

As shown in Figs 6c and 6d, there continue to be similarities in breadth across all groups; however, there are differences in depth of responses across the system palettes. While it should not be assumed that all the Chinese participants had the same experience regarding the earthquake in Sichuan, they did differ in their undergraduate major. As such, it is remarkable that there is a discernible difference in their diagrams that is comparable to a difference between the US (Katrina) and US (MDE) experiences (e.g., engineering major). Where the average for the China (Non-Engineers) had the greatest depth at the intersections of Prevention-Communication and Treatment-Humanist, the China (Engineers) had the greatest depth at the Treatment-Humanist, Treatment-

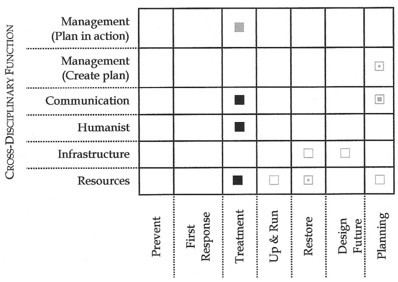

Fig. 6a. System palette diagram for average US (Katrina) team. Key: □ (average less than 0.25 responses), ⊡ (between 0.25 and 0.50), ▣ (between 0.50 and 0.75), ▣ (between 0.75 and 1.0), ■ (between 1.0 and 1.5), ■ (between 1.5 and 2.0).

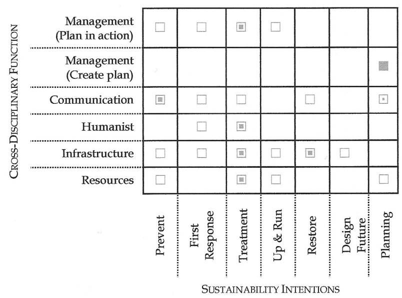

Fig. 6b. System palette diagram for average US (MSE) participant. Key: □ (average less than 0.25 responses), ⊡ (between 0.25 and 0.50), ▣ (between 0.50 and 0.75), ▣ (between 0.75 and 1.0), ■ (between 1.0 and 1.5), ■ (between 1.5 and 2.0).

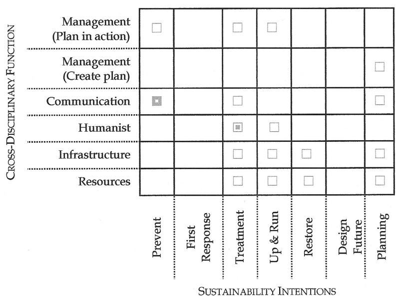

Fig. 6c. System palette diagram for average China (Non-Engineers) participant. Key: □ (average less than 0.25 responses), ⊡ (between 0.25 and 0.50), ▣ (between 0.50 and 0.75), ▣ (between 0.75 and 1.0), ■ (between 1.0 and 1.5), ■ (between 1.5 and 2.0).

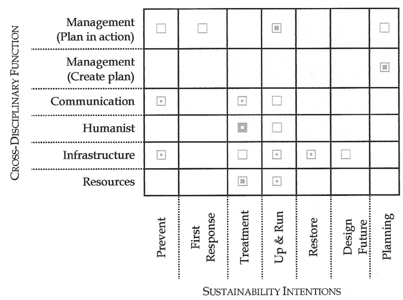

Fig. 6d. System palette diagram for average China (Engineers) participant. Key: □ (average less than 0.25 responses), ⊡ (between 0.25 and 0.50), ▣ (between 0.50 and 0.75), ▣ (between 0.75 and 1.0), ■ (between 1.0 and 1.5), ■ (between 1.5 and 2.0).

Responses, and various planning intersections. In addition, where the US (Katrina) diagram emphasizes the interrelationship between communication needs with Treatment goals, the China (Non-Engineers) diagram emphasizes communication needs with Prevention goals. This may be an influence of their proximity to an actual disaster since participants in this group identified a number of communication challenges about safety education that could minimize the impact of a disaster. Similarly, the Chinese participants identified both pre-disaster and post-disaster issues that may be an influence of their disaster experience. For examples, they expressed concerns about the quality of warning and disaster education systems and a desire to quickly get out of 'the shadow' of the recent disaster.

5. DISCUSSION

Overall, the analyses presented in Figures 4–6 illustrate the utility of the design scenario task and associated coding frameworks in (1) characterizing problem formulation abilities through a cross-disciplinary sustainable system perspective and (2) revealing relevant group differences associated with proximity to a disaster, undergraduate major, and educational experiences that address issues of cross-disciplinarity and sustainability.

Collectively, the Intention, Planning, and Function coding schemes for the issues and expertise task questions paint a picture of an ability to formulate complex, contextualized, and cross-disciplinary sustainable design problems. These coding schemes also highlight opportunities for improving problem formulation abilities. The Intention codes emphasize differences in time, scope, and flexibility regarding goals for designing a disaster relief plan. These codes map to a philosophy of sustainable design that speaks to short and long term needs [20] as well as an empirically derived framework that characterizes increasingly comprehensive understandings of sustainable design [26]. For example, issues coded as Prevention, Restore, or Design for Future may represent a very comprehensive 'social network problem solving sustainable design approach' due to the extremely long time periods involved, the large scope, and the considerable level of flexibility. This may help explain the limited coverage of these kinds of issues across the average participants' responses since participants had limited professional experience. Similarly, issues coded as Treatment may represent a less comprehensive 'reductionist problem solving sustainable design approach' due to the shorter term planning, targeted scope, and limited flexibility. Again, this may help explain the considerable emphasis on Treatment issues for participants with limited experience designing disaster relief systems. This suggests that students may need guidance in developing a broader perspective of the impact of natural disasters and the associated goals for designing an effective disaster relief system [41]. The results suggest similar opportunities for improvement regarding the Planning code analysis.

The Function codes illuminated the breadth and depth of participants' responses across cross-disciplinary system level issues of communication, humanist, resource, infrastructure, and management needs. Integrating these with Intention codes to create system palette representations provided opportunities to understand and critique how participants relate goals (Intention code) to system requirements (Function code). For example, the diagrams in Fig. 6a through 6d suggest that there are opportunities for participants to develop a more comprehensive perspective and set of usable skills. Finally, including both the issues and expertise task questions provided opportunities to triangulate findings and examine how participants associated expertise across multiple system goals or functions.

The coding frameworks also revealed relevant group differences that might be anticipated due to differences in experiences or proximity with a natural disaster, undergraduate engineering major, and guided instruction around cross-disciplinary thinking. For example, while the China groups had similar response patterns for the Intention analyses they had noticeably different responses regarding the Function analyses that may be associated with their undergraduate major. The depth of responses of the US (Katrina) participants as evidenced in the system palette diagrams may be associated with their immersive educational experiences on-site in the Hurricane Katrina disaster zone and triangulates with the content of term papers submitted for this course [23]. Their depth of responses may be indicative of deeper learning, as compared to surface learning. Proximity to a disaster or disaster site also appeared to play a role—China participants' recent disaster experience may have influenced how their responses addressed both pre and post disaster needs while the US (Katrina) participants' responses suggest they were influenced both by their community interactions on site as well as their shared educational experience. Finally, there was a strong difference across undergraduate majors. Participants who were in engineering majors, regardless of being in the US or China, identified similar functional requirements. In particular, the US (MDE) and China (Engineers) participants were more likely to identify infrastructure and management needs while the US (Katrina) and China (Non-Engineers) were more likely to identify communication, humanist, and resource needs.

We conclude the discussion by articulating limitations of this exploratory study. First, background data was not available and as such group comparisons cannot address the influence of individual differences. Similarly, it was not possible to administer the tool as a pre and post-test scenario. Second, the unit of analysis was not consistent across groups because the US (Katrina) participants completed the task as a team and not individuals. Finally, while inter-rater reliability in coding was closely monitored it was not quantitatively assessed. While questions of reliability and generalizability cannot be addressed in this exploratory study, the ability to meaningfully transfer the scenario tool across contexts suggests the tool holds considerable promise and warrants further development.

6. CONCLUSIONS

We conclude with summarizing ways the scenario instrument may be used as a research tool, an assessment tool, and an instructional tool. This goal fits within a research-to-practice framework [42–43].

As a *research tool*, the disaster scenario task and coding frameworks provide a way to empirically analyze problem formulation abilities with a particular focus on cross-disciplinary systems and sustainability perspectives. An added benefit is that the disaster scenario fully embraces a 'grand engineering challenge' and as such might be broadly useful for a variety of settings and instructional goals. The analysis across the four groups suggests the coding scheme is sensitive to relevant group characteristics such as experience with a disaster, guided instruction, and engineering training. At the same time, the analysis suggests the existence of cultural effects and a need to consider whether or not the disaster in the scenario should address a familiar natural disaster that would be relevant for a particular group. Similarly, responses across cultures may provide an opportunity to understand socio-economic, political and cultural perspectives. For example, how might responses compare if the disaster was set in an urban or rural setting, a high income or low-income setting, or a national or international setting? While the process of developing the coding scheme and establishing a reliable coding process is time intensive, the long term benefit is a framework that can integrate cross-disciplinary, systems, and sustainability perspectives. In addition, the integration of task questions that speak to the issues that need to be considered and the kinds of expertise needed on a cross-disciplinary team provide an additional point for triangulating findings.

As an *assessment tool*, the disaster scenario task and coding frameworks may fulfill a need for formative or summative assessment. As a formative assessment tool it may provide an opportunity for class discussion and feedback, as a summative assessment tool it may provide class or program level data on instructional impact. For example, the original goal of this project was an assessment task, however circumstances did not allow an opportunity to collect pre- and post-instruction data. We are currently exploring adapting this tool for a cross-disciplinary cancer prevent program and anticipate the Intention code will transfer but that the Function categories will evolve.

As an *instructional tool*, the disaster scenario task and coding schemes may provide ways to engage students in cross-disciplinary thinking around issues of sustainability. This may complement pedagogies that focus on experiential, inquiry-based, and collaborative learning pedagogies [44–45] by providing students opportunities to confront their own conceptions of design and examining how other students approach formulating cross-disciplinary problems. In a Research-to-Practice Workshop on engineering design, engineering faculty identified a variety of strategies for using research in engineering classrooms: showing research data to students to explain or validate a particular effective engineering practice, using research findings to define course or learning objectives, and having students complete the task and critique their responses in class [42].

The unique value of this set of tools is that cross-disciplinary sustainable systems concepts may be very abstract. Both instructors and students may benefit from seeing an example of characterizing a complex cross-disciplinary sustainability perspective and discussing how this example does (or doesn't) adequately represent important issues. Some ways to translate the instrument into an instructional activity include having students analyze the results and discuss (1) why were Treatment issues so prevalent and what might be the long-term implications of not considering Restore or Prevention issues? (2) how do communication functions in a disaster relief plan relate to being an effective engineer? (3) what would happen if groups could be combined and how might this represent a more cross-disciplinary system approach? and (4) what would be the consequences of identifying people with particular expertise as contributors to multiple aspects of the system (versus just one)?

As a 'grand engineering challenge', the disaster relief scenario represents a situation in which learners are likely to have some prior experience. A final opportunity is to explore ways to connect prior experience to formulating cross-disciplinary problems. In particular, the scenario and associated coding frameworks provide opportunities for students to reflect and internalize broader impact processing skills that are crucial for meeting present and future needs.

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REFERENCES

1. J. Bordogna, E. Fromm and E. W. Ernst, Engineering Education: Innovation through Integration. *Journal of Engineering Education*, **82**(1), 1993, pp. 3–8.
2. R. S. Adams, L. Mann, S. Jordan and S. Daly, Exploring the boundaries: language, roles, and structures in cross-disciplinary design teams. In: J. McDonnell and P. Lloyd (eds), *About Designing: Analysing Design Meetings*, Chapter 19. London: Taylor and Francis Group, 2009.
3. R. S. Adams, L. Mann and T. Forin, *Cross-disciplinary practice in engineering contexts.* Proceedings of the International Conference on Engineering Design, ICED, August, Stanford, CA, 2009.
4. L. L. Bucciarelli, *Designing Engineers.* Cambridge, MIT Press, 1996.
5. J. McDonnell, Collaborative Negotiation in Design: A Study of Design Conversations between Architect and Building Users. In: J. McDonnell and P. Lloyd (eds), *About Designing: Analysing Design Meetings*, Chapter 14. London: Taylor and Francis Group, 2009.
6. R. S. Adams, J. Turns and C. J. Atman, Educating effective engineering designers: The role of reflective practice. *Design Studies*, **24**(3), 2003, pp. 275–294.
7. L. J. Ball and B. T. Christensen, Analogical reasoning and mental simulation in design: Two strategies linked to uncertainty resolution. *Design Studies*, **30**, 2008, pp. 169–186.
8. D. H. Jonassen, J. Strobel and C. B. Lee, Everyday Problem Solving in Engineering: Lessons for Engineering Educators, *Journal of Engineering Education*, **95**(2), 2006, pp. 139–151.
9. F. Johansson, *The Medici Effect: Breakthrough Insights at the Intersection of Ideas, Concepts & Cultures. Cambridge*: Harvard Business School Press, 2004.
10. T. Friedman, *The World is Flat: A Brief History of the Twenty-First Century*. Farrar, Straus and Giroux, 2005.
11. National Academy of Engineering. *Engineering of 2020: Visions of Engineering in the New Century.* Washington DC: National Academy of Engineering, National Academy Press, 2004.
12. R. Harding, *Sustainability in the Curriculum: Why and How?—Keynote Address.* Paper presented at the 10th Annual Australasian Association of Engineering Education Conference: Unfolding Landscapes in Engineering Education, Adelaide, 1999.
13. G. J. McDonnell, Disciplines as Cultures: Towards Reflection and Understanding. In: M. A. Somerville and D. A. Rapport (eds), *Transdisciplinarity: Recreating Integrated Knowledge*. Oxford: EOLSS Publishers, 2000.
14. C. J. Atman, K. Yasuhara, R. S. Adams, T. Barker, J. Turns and E. Rhone, Breadth in Problem Scoping: A Comparison of Freshman and Senior Engineering Students. *International Journal of Engineering Education*, **24**(2), 2008, pp. 234–245.

15. N. Cross, Design cognition: Results from protocol and other empirical studies of design activity. In: C. M. Eastman, W. M. McCracken and W. Newstetter (eds), *Design Learning and Knowing: Cognition in Design Education*. New York: Elsevier Press, 2001.
16. G.Downey, J. C. Lucena, B. M. Moskal, R. Parkhurst, T. Bigley, C. Hays, B. Jesiek, L. Kelly, J. Miller, S. Ruff, J. Lehr and A. Nichols-Belo, The Globally Competent Engineer: Working Effectively with People Who Define Problems Differently. *Journal of Engineering Education*, April, 2005, pp. 107–122.
17. J. Bransford, Guest Editorial: Preparing People for Rapidly Changing Environments. *Journal of Engineering Education*, January, 2007, pp. 1–3.
18. G. Clough, *Educating the Engineer of 2020: Adapting Engineering Education to a New Century.* Washington DC: National Academy of Engineering, National Academy Press, 2005.
19. Committee on Facilitating Interdisciplinary Research, Committee on Science, Engineering, and Public Policy. Facilitating Interdisciplinary Research. Washington, DC: National Academies Press, 2005.
20. J. F. McLennan, *The Philosophy of Sustainable Design*. Kansas City: Ecotone, 2004.
21. Engineers without Borders. URL: http://www.ewb-international.org/
22. Institute without Boundaries. URL: http://www.institutewithoutboundaries.com/
23. D. Wilson, *Experiences of Engineering Students in post-Katrina Service Learning Programs.* Proceedings of the annual Frontiers in Education conference, 2008.
24. A. McKenna, An investigation of adaptive expertise and transfer of design process knowledge. *Journal of Mechanical Design*, **129**(7), 2005, pp. 730–734.
25. J. M. T. Walker, D. S. Cordray, S. Brophy and P. H. King, Design Scenarios as an Assessment of Adaptive Expertise. *International Journal of Engineering Education*, February, 2006.
26. L. M. W. Mann, D. Radcliffe and G. Dall'Alba, *Using Phenomenography to Investigate Different Ways of Experiencing Sustainable Design*. ASEE Annual Conference & Exposition, Honolulu, Hawaii, 2007.
27. C. J. Atman, J. R. Chimka, K. M. Bursic and H. L. Nachtmann, A comparison of freshman and senior engineering design processes. *Design Studies*, **20**(2), 1999, pp. 131–152.
28. K. M. Bursic and C. J. Atman, Information Gathering: A Critical Step for Quality in the Design Process. *Quality Management Journal*, **4**, 1997, pp. 60–75.
29. C. J. Atman, R. S. Adams, S. Mosborg, M. Cardella, J. Turns and J. Saleem, Engineering Design Processes: A Comparison of Students and Expert Practitioners. *Journal of Engineering Education*, 2007, **96**(4).
30. C. J. Atman, D. Kilgore and A. McKenna, Characterizing Design Learning: A Mixed-Methods Study of Engineering Designer's Use of Language. *Journal of Engineering Education*, 2008, **97**(3).
31. L. L. Bogusch, J. Turns and C. J. Atman, *Engineering Design Factors: How Broadly Do Students Define Problems?* Proceedings of the American Society of Engineering Education Annual Conference, 2000.
32. E. Rhone, R. Adams, J. Turns and C. J. Atman, *Assessing IE Students' Preparedness for Practice: Do They Think Broadly?* Proceedings of the Annual Industrial Engineering Research Conference, Portland, OR 2003.
33. J. T. Klein, *Interdisciplinarity: History, theory, and practice.* Detroit: Wayne State University, 1990.
34. H. Nelson and E. Stolterman, *The Design Way: Intentional Change in an Unpredictable World.* New Jersey: Educational Technology Publications, 2003.
35. W. McDonough and M. Braungart, *Cradle to Cradle: Remaking the Way We Make Things.* New York: North Point Press, 2002.
36. V. Goel and P. Pirolli, The Structure of Design Problem Spaces. *Cognitive Science*, **16**, 1992, pp. 395–429.
37. D. H. Jonassen, Toward a Design Theory of Problem Solving. *Educational Technology: Research & Development*, **48**(4), 2000, pp. 63–85.
38. A. L. Brown and J. C. Campione, Designing a community of young learners: Theoretical and practical lessons. In: N. M. Lambert and McCombs, B. L. (eds.), *How students learn: Reforming schools through learner-centered education*, pp. 153–186. Washington, DC: American Psychological Association, 1998.
39. A. Strauss and J. Corbin *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*. Sage Publications, 1990.
40. W. M Hall, *Thinking and planning for the 21st century: A holistic approach to thinking and planning. Federation of Amercian Scientists, 1994*. Retrieved Aug. 28, 2008 from http://www.fas.org/irp/doddir/army/usfk_j2/think.htm.
41. J. Herkert, ABET's *Engineering Criteria 2000 and Engineering Ethics: Where Do We Go From Here?* OEC International Conference on Ethics in Engineering and Computer Science, 1999. Available Online: http://onlineethics.org/CMS/edu/instructessays/herkert2.aspx
42. J. Turns, R. S. Adams, A. Linse and C. J. Atman, Bridging from Research to Teaching in Undergraduate Engineering Design Education. *International Journal of Engineering Education*, **20**(3), 2003, pp. 379–390.
43. J. Turns, R. S. Adams, J. Martin, M. Cardella, S. Mosborg and C. J. Atman, Tackling the Research-to-Practice Challenge in Engineering Design Education: Insights from a User-Centered Design Perspective. *International Journal of Engineering Education*, 2006.
44. National Resource Council. *How People Learn: Brain, Mind, Experience, and School,* Expanded Edition. Washington, DC: National Academy Press, 1999.
45. K. A. Smith, S. D. Sheppard, D. W. Johnson and R. T. Johnson, Pedagogies of Engagement: Classroom-Based Practices. *Journal of Engineering Education*, January, 2005, pp. 1–15.

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