

Enabling safer design via improved understandings of knowledge-related hazards: A role for cross-disciplinarity *

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SUMMARY: *Many accidents arise from knowledge-related hazards. These hazards can lead to catastrophic industrial disasters and “routine” harm. An example of a knowledge-related hazard is knowledge-loss due to employee turnover. It is proposed that safe design requires expertise relating to these and other hazards, even though such hazards are ordinarily associated with non-engineering disciplines. However, rather than trying to enable each designer to achieve expertise in all of the relevant disciplines, it is proposed that curricula might place greater emphasis on enabling the ability to work effectively in cross-disciplinary teams.*

1 INTRODUCTION

It is proposed that cross-disciplinarity is required to achieve safe design. By way of introduction, consider some consequences of “unsafe” design.

Examples of well-known catastrophic industrial accidents include the 1984 Union Carbide accident in Bhopal, India, which is commonly cited as the world’s worst industrial disaster, and the 1986 nuclear power-plant disaster at Chernobyl, Ukraine, which is thought to be the world’s worst nuclear accident.

Poorly informed management and design decisions, typically combined with cost cutting, are often a contributing factor in industrial accidents (Reason, 1990; Kletz, 1994). The 1984 Union Carbide Bhopal accident is estimated to have caused at least 3000 immediate deaths due to a toxic gas leak, 5000 subsequent deaths, and serious injury to approximately 100,000 people. To this day, the site remains highly contaminated, and toxins are continuing to leak into soil and groundwater. Instead of facing litigation and providing compensation, Union Carbide ceased operations in India and refused to attend legal proceedings.¹ The accident had multiple causes, but contributing factors included the design of the plant, failure to heed prior warnings, and failure to transfer safety-critical knowledge to relevant employees.

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Less well known is that only a small minority of industrial fatalities are due to *catastrophic* accidents. Most are caused by *routine* accidents, such as being struck by a moving vehicle or falling from height. In 2001-2002, 297 Australian fatalities were compensated as resulting from workplace activities (NOHSC, 2003a; 2003b). Of these, most of the fatalities were in construction, transport/storage, manufacturing and the business/services sectors. Illnesses attributed to work-related activities account for many more fatalities. From 1998 to 2000, 1172 Australian cases of mesothelioma were attributed to exposure to asbestos (HSE, 2003). It is estimated that in 2001-2002, 2.3 million people in Great Britain had an illness that they believed was due to, or exacerbated by, their current or past employment activities (HSE, 2003). In addition to harm done to human lives, any estimate of the total cost of unsafe industrial practices would need to take into account the harm caused to water supplies, soils, plant and animal life and other aspects of the biosphere.

2 KNOWLEDGE-RELATED HAZARDS

Knowledge-related hazards are understood here as hazards that arise from, or could be controlled by, activities that broadly fall under the umbrella of the discipline known as knowledge management. Several of the many various knowledge management activities are relevant, but most relevant here is

¹ Union Carbide was later renamed Eveready Industries, and subsequently merged with Dow Chemical.

the generation, storage, transfer and application of knowledge. To illustrate one of the connections between knowledge management and safety, it can be readily seen that certain industrial accidents, such as Union Carbide Bhopal, would be avoided if knowledge from previous incidents had been generated, stored and applied.

Considerable prior research has addressed attempts to characterise knowledge according to certain dichotomies (perhaps false) including *tacit-explicit* and *declarative-dispositional*. Tacit knowledge has been variously described as being subconsciously understood and applied, difficult to articulate, developed from direct experience and action, and "usually shared through highly interactive conversation, storytelling, and shared experience" (Zack, 1999); whereas explicit knowledge is that which can be readily codified, transferred and replicated. Knowledge has also been characterised as declarative or dispositional, where declarative knowledge refers to knowing about something, and dispositional knowledge refers to the ability to do something (Brown & Duguid, 2001).

While dichotomisations such as the above may tend to oversimplify, they may nevertheless be helpful for the purpose of understanding some of the following examples of knowledge-related hazards.

3 KNOWLEDGE-RELATED HAZARDS CAN ARISE FROM EMPLOYEE TURNOVER

Many organisations value the collective knowledge of their employees among the organisation's most important assets. However, when employees leave organisations, their tacit knowledge can go with them. For example, at many sites in Australia, many control operator employees have held their current positions for at least 10 years, and some for 25 years or more (Forest, 2002). If their knowledge is not somehow "captured" within the next five to 10 years, when these senior employees retire, much knowledge will leave with them. Thus many sites have major challenges ahead as they attempt to manage the hazards that arise due to knowledge-loss from employee turnover.

4 KNOWLEDGE-RELATED HAZARDS CAN ARISE FROM AUTOMATION

Knowledge-loss due to automation can exacerbate the above hazards. Research indicates that knowledge about the design and operation of a plant can be lost when systems are automated, and that skills and plant knowledge are lost as the levels of automation are increased (Bainbridge, 1987). Many system designers automate tasks in the belief that it may help to minimise the harm that can be done by "error prone"

human operators. Bainbridge described two issues that arise from tasks being automated. Firstly, design errors (or latent errors) can be a more significant cause of problems than they would otherwise be. Although automated systems are designed to be safer and to make operators' tasks easier, they tend to be more difficult to operate during emergency situations. Secondly, the tasks that are not automated (because they are difficult to automate) are usually also difficult for an operator to perform. As James Reason put it: "In their effort to compensate for the unreliability of human performance, the designers of automated control systems have unwittingly created opportunities for new error types that can be even more serious than those they were seeking to avoid" (Reason, 1997). Reason referred to this as "clumsy automation" – systems that result from designers' misguided efforts to minimise human input into the control loop.

A negative consequence of full automation is sometimes characterised as the "out-of-the-loop" problem – a situation where operators have less interaction with their systems, leading to reduced awareness about the state of the system, and less control. Some prior research suggests that partial-automation may be preferable to full-automation in systems such as these (Endsley, 1995; Endsley & Kiris, 1995). For this reason, some have advocated the adoption of a framework involving "human-machine cooperation" (Hoc, 2000). Rather than some tasks always being undertaken by machines, and others always being undertaken by humans, the human-machine cooperation approach requires that the functions allocated to computers and humans are constantly changed. Experimental testing of this approach in aircraft traffic control has produced encouraging results (Hoc & Debernard, 2002). It is thought that an additional benefit is that when tasks are dynamically allocated between operators and computers, operators might continually retain, use and share more knowledge while performing their normal daily activities. Issues associated with automation and knowledge-loss are discussed in more detail in Moulton & Forest (2005). Research suggests that many of the known strategies for facilitating knowledge transfer may have unknown or limited effectiveness. A further relevant implication is that newer-style control interfaces may be inherently less suited for visualising/enabling the designers' understandings of the system during the specification, design and testing stages, and the operators' understandings of the systems when the systems are commissioned.

5 KNOWLEDGE-RELATED HAZARDS CAN ARISE FROM RELIANCE ON ALARMS

Another hazard that results from technological advances is related to the increasing reliance on

alarms. To illustrate, explosions at the Esso-Exxon gas plant at Longford caused the death of two people, injuries to eight, and losses to Victorian industry of more than \$1 billion. The ensuing Longford Royal Commission found that a contributing factor was that operators had been routinely responding to hundreds of alarms per day (Dawson, 1999). Subsequent investigations revealed that in one “process upset”, 8500 alarms occurred within a 12-hour shift (Hopkins, 2000). Many of the alarms were considered to be “nuisance alarms”, as they were indicating temporary fluctuations in the state of the plant. These alarms did not require any action to be taken (other than muting the alarm) because the system would usually return to a state that would adequately meet the specified production criteria without intervention. Thus the operators’ attention was continually being drawn to elements of the commercial aspects of the operation to ensure that the output of the plant did not fall outside the desired specifications, without emphasis on knowledge that some responses to the many alarms were in fact extremely hazardous.

While the above is an example of a literal “alarm driven environment”, it serves to illustrate how similar hazards may arise in situations where employees are reacting by the minute or hour to daily productivity-related “crises”, because constant attention to such crises tends to obscure the need to respond appropriately to “real” or safety-related crises when they arise.

6 WORKPLACE PROGRAMS SUCH AS AUDITS AND INCIDENT REPORTING DO NOT RESOLVE ALL OF THE PROBLEMS THAT ARISE FROM DESIGNS THAT ARE INTRINSICALLY UNSAFE

In some cases organisations have attempted to improve safety in the workplace by way of isolated programs targeted at particular “late-stage” aspects of safety, for example:

1. monitoring accident and near miss statistics
2. spot checks
3. measures designed to encourage employees to wear protective equipment
4. “think safe” programs and other attempts to encourage safety culture.

Programs such as these are effective in many situations. For example, Dupont, reportedly the

nastiest corporate air polluter in the United States (CTIS, 2008), would no doubt have a far worse track record if not for the implementation of various successful workplace safety programs (which it now sells). Notwithstanding, such programs face major challenges when employees are working with equipment or processes that is, due to the underlying design, intrinsically hazardous.

In addition, high degrees of non-compliance with incident reporting activities can be experienced because incidents are sometimes used by managers to assess or measure employees’ performance. The comments in table 1 highlight some of the issues.

These comments indicate that employees may sometimes fail to report their own or colleagues’ mistakes, problems or near-miss incidents due to in part to perceptions that their reports are not monitored, nor changes implemented, and in part due to the discomfort that may arise from reporting errors made by their workmates (or superiors). In addition, employees may be unwilling to report their own errors if the organisation is likely to discipline or dismiss them. Findings such as these raise concerns relating to the interpretation and widespread reliance upon of statistics about incidents and near misses.

The Esso-Exxon Longford gas plant disaster mentioned above serves to illustrate additional challenges relating to safety audits. After the Exxon Valdez oil spill disaster in Alaska in 1989, Exxon introduced guidelines to require hazard and operational ability (HAZOP) studies for all plants. A HAZOP for the Longford plant was planned for 1995, but was not conducted. A safety management audit conducted by Exxon six months before the accident should have picked up numerous failings in training, operating procedures, risk identification, risk analysis, risk management, documentation, data and communications. The audit also failed to report that the HAZOP that had been scheduled for 1995 had not been undertaken (Dawson, 1999). The Longford Royal Commission found that instead of ensuring safe equipment and procedures, Esso’s management had decided to encourage a “safe mindset” among employees, and had asked them to “take more care” when performing their duties (Hopkins, 2000).

Awareness of the dangers of knowledge-loss has led to organisations implementing workplace programs to attempt to convert tacit knowledge to codified knowledge, in the hope that if knowledge can be

Table 1: Operators’ comments related to incident reporting and safety culture.

<p>“Not anymore – operating errors result in sacking therefore a cover-up mentality exists”</p> <p>“Discipline enforced by managers for near miss”</p> <p>“Procedures exist but supervisors resistant to accept reporting – they hinder the process”</p> <p>“Purely a paper shuffle”</p>
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codified, the knowledge might then be incorporated into expert systems or transferred to other employees via formal training. However, many attempts to impart tacit knowledge to decision-makers via a process of codification may prove to be futile. Some have argued that some aspects of tacit knowledge can be transferred only through face-to-face contact (Roberts, 2000), and that converting tacit knowledge to declarative knowledge is less effective for achieving knowledge transfer than aligning the goals and practices of employers and employees (Brown & Duguid, 2001). Nonaka & Nishiguchi (2001) held that most knowledge is created not by individuals, but by interaction and dialogue among several people, and knowledge is created not just through human interaction, but by real-time interaction in specific physical, virtual and mental contexts. If such viewpoints are correct, it is possible that certain workplaces may have specific characteristics that cause formal methods of knowledge transfer to be inadequate. If this is the case, the workplace programs' attempts to codify their more experienced employees' knowledge are to some extent based on flawed premises.

7 SAFE DESIGN IS OBLIGATORY ACCORDING TO VARIOUS LAWS AND REGULATIONS

In many parts of the world, various laws, regulations and standards stipulate that organisations can be found liable for harm caused by unsafe operations. (This is still the case despite many multinational corporations' concerted efforts to hasten the worldwide trend toward "self regulation".) In New South Wales, organisations must operate according to a multitude of rules concerned with employers' obligations with respect to negligence and duty of care. Statutes, regulations and codes relating to employees in NSW include the Occupational Health and Safety Act 2000 (NSW) and accompanying Occupational Health and Safety Regulation 2001 (NSW) – among other things, these specify employer obligations for reducing workplace hazards, so that the health and safety of employees is managed, safe equipment and facilities are provided and maintained, safe storage, handling and transport practices are ensured, and adequate training and supervision is provided. For example, the Protection of the Environment Operations Act 1997 (NSW) stipulates fines of up to \$1 million if a corporation wilfully or negligently harms or is likely to harm the environment.

More specifically in relation to engineering design and manufacturing, Section 18 of the Australian Occupational Health and Safety Act 1991 (Commonwealth) states:

(1) A manufacturer of any plant that the manufacturer ought reasonably to expect will be

used by employees at work must take all reasonably practicable steps:

(a) to ensure that the plant is so designed and constructed as to be, when properly used, safe for employees and without risk to their health; and

(b) to carry out, or cause to be carried out, the research, testing and examination necessary in order to discover, and to eliminate or minimise, any risk to the health or safety of employees, that may arise from the use of the plant; and

(c) to make available to an employer, in connection with the use of the plant by employees at work, adequate information concerning:

(i) the use for which it is designed and has been tested; and

(ii) details of its design and construction; and

(iii) any conditions necessary to ensure that, when put to the use for which it was designed and tested, it will be safe for employees and without risk to their health.

Section 11 of the Occupational Health and Safety Act 2000 (NSW) states:

(1) A person who designs, manufactures or supplies any plant or substance for use by people at work must:

(a) ensure that the plant or substance is safe and without risks to health when properly used, and

(b) provide, or arrange for the provision of, adequate information about the plant or substance to the persons to whom it is supplied to ensure its safe use.

Several sections of the Occupational Health and Safety Regulation 2001 (NSW) place obligations on designers, including:

- S 86 Designer to identify hazards
- S 88 Designer to assess risks
- S 88 Designer to review risk assessment
- S 89 Designer to control risks
- S 96 Designer to provide information
- S 97 Designer to obtain information.

The various statutes, regulations and codes of practice apply to organisations of all sizes; even small organisations must maintain OHS records and nominate a senior manager (or equivalent) for OHS responsibility. The AS/NZS 4360 risk management standard (AS/NZS, 2004) provides a guide for reducing risk through all stages in the life of a product or process. Laws, codes, standards rules and regulations have played a significant role in reducing gross and reckless acts of harm to people and the environment, but it is readily apparent that these approaches to achieving safe design are, by and large, a long way from ensuring truly sustainable design.

The Australian Safety and Compensation Council (ASCC), made up of representatives from each state, replaced the National Occupational Health

and Safety Commission in 2005, and is currently attempting to achieve greater regulatory consistency across Australia, and greater awareness of the importance of safe design (Creaser, 2008). The ASCC recommends that designers should demonstrate the ability to apply relevant data on human abilities and behaviour, and designers should have “the ability to integrate knowledge from a range of sources and disciplines” (ASCC, 2006, pp. 22). In addition, the ASCC indicates that many design projects are too large and complex to be fully understood by one person, and hence a design team may need to include people from different disciplines.

In practice, to meet their legislative obligations, designers participate in multidisciplinary meetings to consider cross-discipline issues. The meetings are attended not only by designers, but also other stakeholders including construction, operations, maintenance and clients.

8 SUSTAINABLE DESIGN EMPHASISES THE “LONG-TERM” ASPECTS OF SAFE DESIGN

Sustainable design is design that attempts to *ethically balance* its various impacts. Several fields, including engineering, built architecture and industrial design, have seen a significant trend towards concepts associated with sustainable design.

Design not only impacts upon a product’s cost and functionality, but can also impact upon its maintainability and other issues such as health, education, ecology, government or crime. Seen this way, sustainable design is not new. Examples of it can be found in the development of devices and processes that were intended to reduce hazards imposed by machines of the industrial era.

Design is sometimes viewed as a process that selects between various design objectives, or trade-offs. When viewed within this framework, it is apparent that the setting of the objectives is a key driver. Objectives can be set so that the outcomes are more likely to include processes, systems or products that benefit society in the long-term, taking into account the whole life cycle. In this way, sustainable design can be seen as an alternative understanding of safe design that places greater emphasis on wider and longer-term implications.

9 CROSS-DISCIPLINARITY

For the purposes of this discussion, *multi-* and *inter-*disciplinarity are treated along similar lines to those provided by Nicolescu (2002), whereas different understandings of transdisciplinarity are provided here. Very briefly, I differentiate each of these from the others as follows:

Multidisciplinarity refers to the study of something in several disciplines at the same time. A multidisciplinary approach is taken when practitioners of different disciplines work side-by-side to solve a problem. For example, a multidisciplinary team that designs a control system might include engineers, psychologists and mathematicians.

Interdisciplinarity is the transfer of methods from one discipline to another. For example, an interdisciplinary approach might be taken by a team that develops an algorithm based on principles of evolutionary biology.

Transdisciplinarity is said by Nicolescu to be simultaneously between, across and beyond the disciplines. Transdisciplinarity has been characterised as something that is “integrative”, that “combines disciplines”, and “cuts across the boundaries” that exist between orthodox disciplinary understandings (eg. Horlick-Jones & Sime, 2004). Different understandings of transdisciplinarity are apparent in the literature. One understanding characterises people in different disciplines as having different “levels of reality” – for example, a psychologist’s account of a designer’s behaviour addresses it at level that is different from that which would be found in an account of behaviour that is written by a biologist or an economist. A transdisciplinary approach might attempt to combine discipline-specific understandings to create new understandings beyond those achieved by placing the disciplinary understandings alongside each other. Another view of transdisciplinarity sees it as an *extension* of knowledge, or as something which transcends discipline-specific knowledge.

Cross-disciplinarity appears to be commonly used as a catch-all term to encompass any of the below, or loosely refer to the study of things that belong to more than one discipline.

In the following two sections, it is anticipated that design will impact not only on a product’s cost and functionality, but may also impact on areas such as health, education, ecology, government or crime. However, regardless of whether this view is accepted, a question still arises as to whether a truly cross-disciplinary approach to design requires knowledge across not only the disciplines of engineering and management, but also disciplines such as health, education, economics, psychology and law.

10 SAFE DESIGN CAN REQUIRE CROSS-DISCIPLINARY EXPERTISE

Safe design is understood here as design that prefers a balance of processes, materials and products that enhance short- and long-term safety. For example, safe design may prefer a process that reduces risks of injury or ecological harm, throughout the life cycle

of the object. Safe design may be economically sound in the long-term, as it emphasises efficiency and maintainability. In contrast, unsafe design typically produces items that are costly or risky to modify or maintain, which cause injuries or other harm at one or more stages of the life cycle.

According to the National Occupational Health and Safety Commission (2004), design issues were definitely, probably or suggestively involved in 50% of 210 identified Australian workplace fatalities. In addition, it was found that design contributes to more than 30% of work-related non-fatal serious injuries.

Safe design is not just important for domains that are typically associated with "safety-critical" systems, for example, nuclear and aviation. The principles of safe design can extend to all engineered products (including things such as databases and websites).

An additional challenge when designing or modifying plants is that engineers are frequently in a position where there are significant constraints on their ability to obtain sufficient information about the operations and operators of the plant. In some cases, the complexity is such that it is not reasonable to expect a designer to consider every possible scenario that could arise in subsequent operations or from subsequent modifications – in many cases, the number of possible scenarios is unbounded. Further, designers frequently work with oversimplified models of operator decision-tasks (Toft et al, 2003).

Perrow (1984) suggested that designers should look beyond the conventional explanations that are given for accidents (such as operator error or poor design) and to consider explanations in terms of system characteristics. A pre-accident event might thus be characterised as an operator-interface subsystem failure, instead of as an operator error.

Rasmussen & Pedersen (1984) described two types of decision-making error – active errors and latent errors. While active errors can be thought of as those that are made by operators when faced with a new or unstable situation shortly before an accident, latent errors can remain hidden within the system for many years before they become apparent, and are typically attributable to decisions made by designers, constructors, managers and maintenance staff.

Research has shown that when ergonomic principles are included in the engineering design phase, the resulting systems have higher levels of productivity, efficiency, safety and user-satisfaction (Norman, 1988; Kirwan & Ainsworth, 1992; Mayhew, 1992; Jordan, 1998). Toft et al (2003) argued that engineers must develop a good understanding of ergonomics, as this is essential for understanding the relationship between design and human error. A similar argument could be put that engineers should not rely on oversimplified models of human behaviour, and must develop a good understanding of factors that affect people's decision-making.

The underlying causes of accidents are often many and complex, but relatively simple and pragmatic approaches exist for improving safety. Safety is improved by directing efforts toward the creation and maintenance of an effective safety culture that includes the following features (adapted from Reason, 1997): (a) managers have responsibility for organisational safety, and organisational safety is discussed at all regular top-level meetings; (b) incidents and losses due to unsafe acts are measured and reported; and (c) an individual is appointed as responsible for collating, analysing and disseminating safety-related information, and this individual is provided with enough resources to perform these duties. However, an effective safety culture also includes essential elements that are not so easily mandated, such as shared safety-oriented beliefs, values and priorities, and shared understanding of the value of lifelong learning.

It is apparent that many issues must be considered when attempting to build an improved understanding of the role of decision-making in industrial accidents. Increased levels of automation are resulting in the loss of safety-critical knowledge. As discussed, automation may also be hindering the transfer of knowledge between employees, and alarms are now taking a more prominent role in determining the activities that are undertaken. Changes in many workplaces mean that newly employed employees gain their experience in ways that are different, perhaps less hands-on, from the ways that employees of previous generations gained their experience. Newer managers are similarly not able to gain experience in the same ways as older managers. Similar changes are occurring among designers. While at the same time, system designers require more sophisticated models in order to achieve safer designs.

More recently there has been a shift towards multidisciplinary design approaches to improving safety. An example is an approach advocated by NSW Workcover: CHAIR (Construction Assessment Hazard and Implication Review). CHAIR is a process that brings designers of different disciplines together with other stakeholders to develop a design that reduces construction, maintenance, repair and demolition safety risks (WorkCover, 2001). Its rationale dates back to a study that found that nearly two-thirds of the injuries and fatalities on construction sites can be traced to design and planning decisions (Churcher & Alwani-Starr, 1996). A case study indicates that a participant reported "significant benefits emerged from the process. In particular participants were forced to think outside their own sphere of expertise and how their design decisions impacted on other stakeholders" (WorkCover, 2001, pp. 24).

11 WHO IS RESPONSIBLE FOR SAFE DESIGN?

Safe design involves the mitigation of various “domains” or “levels” of hazards. To understand who is responsible at various domains, it is useful to consider the various roles and responsibilities of the following groups.

First, there are the elected politicians, government employees, professional associations and other stakeholders who provide input into decisions concerning the creation and enforcement of laws, regulations and standards.

Second, there are the managers and other people who make decisions relating to things such as purchasing, maintenance, recruitment and training.

Third, there are engineers and designers who physically design and build the products and processes.

Fourth, there are drivers, pilots, operators, scientists and medical practitioners/nurses etc. who work at human-machine interfaces.

Fifth, there are the people who consume products or are otherwise affected by industrial activities – these people are typically referred to as consumers or “the general public”. This group or “domain” is also responsible for the election of key members of the first group, the elected politicians.

A principle of safe design is that it begins *early* in the process. It is not sensible to point to one of the above groups of people, for example, the engineers, and attempt to assign to them the sole responsibility for safe design. Safe design is clearly also the responsibility of the first and second groups, and perhaps, by indirect means, the fourth and fifth.

12 ENABLING CROSS-DISCIPLINARITY

A review of the literature reveals a commonly held view that a solution to unsafe engineering design is to teach psychology, or ergonomics, to students of engineering. However, it is possible that such attempts to cram more material into engineering curricula, to some extent, arise from a misunderstanding. To illustrate, let us return to the question of whether the legacy of pollution and injury caused by the 19th century industrial age should be understood as being solely due to deficiencies in engineering. The question raises issues about the prevailing attitudes of the time, as well as regulatory environments, class systems of labour, health practices, and levels of education of employees and the wider community. Would it be fair to claim that the widespread harm that resulted from unsafe industrial practices was solely the fault of the engineers? Similar questions are relevant for many of the modern-day hazards that are attributed to “poor engineering”.

Some experts hold the view that traditional instruction methods are not adequate to equip future generations with the knowledge, skills and attitudes they will need to meet the demands placed on them (eg. Mourtos, 2006). Their arguments typically run along the following lines: engineers who employ improved methods in the design of machine-human interfaces increase a system’s usability and productivity (Mayhew, 1992); engineers who understand “human factors” reduce the likelihood of human error, and this results in safer, more efficient designs (Wickens, 1998); thus future engineers should be skilled in assessing not only the operational specifications, but also, the impacts on users and of the system at all stages of its life cycle; hence educators of engineers should develop graduates with attributes and abilities beyond those of engineering professional practice, in effect, graduates who are skilled in disciplines beyond what is traditionally thought of as the engineering discipline.

Another argument runs as follows. Currently, several disciplines hold elements of practice that are relevant to socially responsible design. Frequently, these elements are known by other names and obscured by context and jargon. Due to the different “languages”, translating elements of knowledge from one discipline to another presents difficulties. Proponents of this argument typically claim that transdisciplinarity would be achieved by extracting the relevant elements from each discipline, and creating a new “transdiscipline” (Ertas et al, 2003). Supposedly, this would be accomplished by extensively studying each of the disciplines, identifying common aspects, and weaving them into a new transdisciplinary model.

It remains to be seen whether the above arguments are sustainable. It seems possible that they arise from different understandings of transdisciplinarity. However, the arguments do, nevertheless, serve to highlight some of the relevant issues. The curricula of few engineering faculties explicitly acknowledge a transdisciplinary model, but it is apparent that the underlying concept is implicit in many curricula, perhaps using differing nomenclature (eg. Evans et al, 2007).

It is interesting to note that many students seem to be aware that their engineering knowledge is limited in certain areas.

Table 2 provides some examples. As can be seen, these students seem to readily admit to “not having all the answers”. It would be interesting to examine whether these qualities are seen to the same extent in experienced practising professionals. It is proposed that these students may be at a good stage of development to undertake learning activities that draw from cross-disciplinary sources of expertise. It is possible that efforts to enable greater adoption of principles of transdisciplinarity might

Table 2: Engineering students' comments.

"As my internship progressed I realised the importance of making sure I processed and understood everything that my colleagues told me. Asking questions in order to utilise other people's experience and knowledge became an integral factor in satisfactorily completing my work and in my learning experience."

"My first design in this project was a disaster ... I started working on trying to build things from scratch basically, stuff that would have taken months to complete."

"I had a tendency to dive into projects without much thought and depth into research or even understanding, I just wanted to see things working."

"I've learnt that as an engineer it is important that you don't become too specialised in one area."

"... to help me improve not only my technical knowledge, but my practical abilities within a group and workplace ... Nobody can have perfect technical knowledge, practical abilities, or communications skills."

be more successful if directed towards students than if directed towards professionals who already have years of experience. It is also possible that internships, as compared to the classroom, are more suited to facilitate a shift towards transdisciplinarity. Many professions including education, dentistry, engineering, law, medicine, nursing, psychology and sociology seek to develop competence through internships, and internships are taking an increasing role in professional development. The effects of internships on learning has been the subject of research at UTS (Moulton & Lowe, 2005), and employers' perceptions of internship students' performance with respect to ABET criteria and safety has been the subject of research at locations such as the Arizona State University (Haag et al, 2006) and the Quebec Occupational Health and Safety Research Institute (Gauthier & Benoit, 2002). Given the effort that is already being expended on attempts to maximise internship outcomes, it may be very fruitful to specifically investigate the relationship between transdisciplinarity and internship-learning.

Aspects of transdisciplinarity are seen in the philosophy of *scholarship of engagement*. Several significant and influential schools of thought embody the central concept of scholarship of engagement, but refer to the concept using different terminology such as *service scholarship*, *professional service* and *outreach*. This approach stems from a belief, articulated in Boyer's well known 1990 Scholarship Reconsidered report, that if universities cannot help students to better understand the interdependent nature of the world, "each new generation's capacity to live responsibly will be dangerously diminished" (Boyer, 1990).

Truly safe design is perhaps more an aspiration than an achievable outcome – the same could be said of "perfect" design. Regardless of whether it is accepted that safe design requires transdisciplinarity, it should be apparent that long-term safe design requires understandings that arise from more than one discipline. However, this in itself does not imply that engineering curricula should include more psychology or ergonomics or law or whatever. No single person can know it all. The answer may be that

safer design is best achieved by multidisciplinary teams. If this is the case, educators might consider placing greater emphasis on enabling graduates' abilities to "converse" with those other disciplines. To some extent this may already be addressed by elements of curricula that focus on communication skills. However, further research may help to determine whether it is beneficial to connect communication-enabling learning activities with cross-disciplinary design contexts.

13 CONCLUDING REMARKS

Design that fails to consider knowledge-related hazards can become a causal factor in industrial disasters and routine harm such as spinal injuries, damage to lungs, and degradation of the environment. Traditional approaches to improving safety have led to significant improvements in many areas, but there are some areas where traditional approaches have proved to be inadequate. Safe design can require knowledge across diverse disciplines including engineering, economics, health and psychology. As an alternative to attempting to enable all of the required skills and knowledge in each designer, it is proposed that curriculum developers might place greater emphasis on enabling the skills and abilities that are required to work in cross-disciplinary teams.

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