AC 2007-892: EXPERIENCES OF SUSTAINABLE DESIGN AMONG PRACTICING ENGINEERS ? IMPLICATIONS FOR ENGINEERING EDUCATION

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Experiences of Sustainable Design among Practicing Engineers – Implications for Engineering Education

Introduction

An understanding of sustainable design will be essential for engineers to practice responsibly in the future. What sustainable design means in practice is a contested issue, varying between engineering disciplines, industry sectors and even individual practitioners. How then can we, as engineering educators, encourage and teach both current professional engineers and engineering students about sustainable design.

This paper reports on the results of an empirical study investigating qualitatively different ways that sustainable design has been experienced by practicing engineers. The different ways of experiencing sustainable design were found using a qualitative research method known as phenomenography. This research method revealed the critical variations in the ways twenty-two practicing engineers described their experiences of sustainable design in one-on-one interviews. An in depth description of the research method and the processes undertaken in this research is presented in[1]. This current paper presents an in depth discussion of the results and the implications they have for the practice of sustainable design, and for engineering education.

Five different ways of experiencing sustainable design were found; sustainable design as 'solution finding', 'reductionist problem solving', 'holistic problem solving', 'social network problem solving, and 'a way of life'. Descriptions of each of these ways of experiencing sustainable design are presented, including illustrative quotes from the practicing engineers, as well as an overall hierarchy demonstrating the relationships between the ways of experiencing sustainable design.

By understanding how different people have experienced and conceptualize sustainable design within engineering practice, recommendations are made for how to educate engineering students about sustainable design. Implications for the practice of sustainable design are also made.

Background – Sustainable Design

Sustainable design is one of the major challenges confronting engineering. Some professionals see sustainable design as the addition of some environmentally or socially beneficial features to a traditional design, or trying to reduce the environmental and social impacts of a current design. Others see it as a completely new framework for doing design, and for designs to help regenerate environmental and social systems[2]. One of the reasons behind this confusion is that sustainable design is a movement that is actively defining itself, its principles, components and philosophy[2]. "Like any immature individual, sometimes it seemingly contradicts itself or seems unclear or even irrational" (p3).

Sustainable design differs from traditional design in its results, its rationale and its processes[2]. The traditional design process in general is cyclic in nature, where designers work back and forth

between a set of needs or requirements and a series of interim solutions until a final solution is found[2]. Traditionally the requirements of a design centered on cost, functionality, safety and aesthetics, with little attention paid to the wider implications of the design. Design was based upon a linear, cradle to grave paradigm. Raw materials are extracted and made, manufactured into products, transported to consumers to use, then disposed of in a 'grave', usually in landfill. This type of design paradigm dominates modern design and manufacturing; by some accounts more than ninety percent of materials extracted to made products for end users become waste almost immediately, with the product itself often not lasting much longer[3]. It is often seen as cheaper to buy a new product than repair an old one. Further, many products in this paradigm are even designed with a planned obsolescence, designed to be used by a consumer for a few years then discarded for the 'new' model.

The first change to this traditional design paradigm in moving toward sustainable design occurred with the focus on eco-efficiency. While it can be argued that eco-efficiency had its roots in early industrialisation[3], it has been since the 1992 Rio Earth Summit and Agenda 21[4] that industries across the globe have started to embrace the concept. It was officially coined as a term by the Business Council for Sustainable Development in 1997[3].

Eco-efficiency itself is based on the idea of doing more with less, doing more with the resources that are consumed, generating less waste and pollution, using renewable rather than non-renewable resources, and trying to minimize the harmful affects on human health and the environment[3]. All resources come from either the Earth's crust or the Bio-sphere, and are then processed into raw materials, used in manufacturing systems to create goods and services, then transported to consumers to be used. At the end of use, goods are either recycled, or placed back into the Earth's crust in landfill, or into the Bio-sphere as pollution. Eco-efficiency tries to maximize the utilization of goods and services (V), while minimizing the impact to the Earth's crust and the Bio-sphere (I).

In their book *Cradle to Cradle*, McDonough and Braungart[3] question the goal of efficiency in "a system that is largely destructive"(p63). Destruction, they argue, is generally more visible and easier to stop, whereas efficient destruction is harder to detect and thus harder to stop. From a philosophical point of view, "efficiency has no independent value: it depends on the value of the larger system of which it is a part… if the aims are questionable, efficiency may even make destruction more insidious" (p65). Efficiency can be good, but only within an overall system that is replenishing, rather than destructive. As long as humans and their systems are seen as being 'bad'[5], then the ultimate goal of eco-efficiency is zero: zero wastes, emissions and 'ecological footprint'[6]. But, as McDonough and Braungart[3] ask, what would it mean to be 100 percent good?

One outcome of this thinking is eco-effectiveness. "You might start to envision the difference between eco-efficiency and eco-effectiveness as the difference between an airless, fluorescent-lit gray cubicle and a sunlit area full of fresh air, natural views, and pleasant places to work, eat, and converse"[3](p76). Eco-effectiveness is about working on the right things, products and systems, rather than trying to make the 'wrong' ones less 'bad'. "It is far more powerful to design a process that does not require energy than one that has been optimized to use as little energy as possible"[2](p88). Eco-effective design 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. This is considered within

the entire system – societal, economic and environmental – where the made thing, and way of making things, are parts. From an eco-effective paradigm, designs should include[3](p90-91):

- Buildings that produce more energy than they consume and purify their own waste water;
- Factories that produce effluents that are drinking water;
- Products that, when their useful life is over, do not become useless waste but can be tossed onto the ground to decompose and become food for plants and animals and nutrients for soil; or, alternately, that can return to industrial cycles to supply high-quality raw materials for new products;
- Transportation that improves the quality of life while delivering goods and services;
- A world of abundance, not one of limits, pollution, and waste.

Building on this, McLennan[2] puts forward the following definition of sustainable design: "Sustainable Design is a design philosophy that seeks to maximize the quality of the built environment, while minimizing or eliminating negative impact to the natural environment." Sustainable design is seen as a philosophy, an approach to design that can be applied to any object or project. It tries to enhance quality which as McLennan (p5) argues is about "creating better buildings for people, better products for our use and better places to inhabit". The purpose of design, he argues, is to create physical artifacts that benefit people, and sustainable design tries to do that using a wider, more holistic approach. Finally with the definition, he argues that the ultimate goal of sustainable design is not just to reduce the impact of the design on the environment, but to either remove it all together, or to go a step further and have a restorative effect on the environment.

Overview of Results – Categories of Description

This section presents the qualitatively different categories of description of sustainable design that were developed from the twenty-two interview transcripts. Five categories were developed, as seen in Figure 1, each representing a qualitatively different way of experiencing sustainable design. Each category includes a short description, a diagrammatic representation, and an expanded description with illustrative quotes from the transcripts. All names of subjects given in this paper are pseudonyms. The page numbers after each quote refer to the pages where the quotes appeared in the transcript. The quotes are used to exemplify and clarify the categories. They are however only a subset of the whole interview, and it should be remembered that the categories were developed from the interviews as wholes, and not just from the specific quotes given. Also, not every participant is represented as the quotes were selected to illustrate the features that distinguish each category. Finally, the term 'client' that is used throughout the categories is a general one, and refers to the body that has engaged the designer to carry out the design work. Different designers may carry out completely different work for different clients, but they are always retained by someone, be it a private company, the government, or consumers.

Category Name	Description
Solution Focused	
Category 1 Solution Finding	Sustainable design is finding a solution, either a product or process(es), to satisfy a client's declared requirements while decreasing the associated environmental, social and economic impacts.
Problem Focused	
Category 2 Reductionist Problem Solving	Sustainable design is the process of identifying and solving a client's problem by taking a reductionist approach to making decisions that each decrease the associated environmental, social and economic impact.
Category 3 Holistic Problem Solving	Sustainable design is the process of identifying and solving a client's problem holistically on a systems level, to increase the environmental, social and economic value of the solution.
Social Network Focused	
Category 4 Social Network Problem Solving	Sustainable design is the process of identifying and solving a client's problem as part of a network of wider problems facing society to increase the environmental, social and economic value of the solution to both the client and society.
Category 5 A Way of Life	Sustainable design is a way of life where all design problems, professional and personal, are solved to increase the environmental, social and economic value of the outcome to both the individual and society.

Figure 1: Outcome Space for Sustainable Design

Category 1: Sustainable Design is Solution Finding

Sustainable design is finding a solution, either a product or process(es), to satisfy a client's declared requirements while decreasing the associated environmental, social and economic impacts. (n=5)

The focus of this category is on finding a solution to a client's declared requirements. These requirements are already identified by the client and on the whole are usually non-negotiable, although a few may be negotiable in certain cases. The design process is bounded by these requirements, thus reducing the range of possible options that the designer is able to consider.

The solution is in terms of either the final physical *product* or changes to the technical and or human *processes* involved in producing the final physical product. The product or processes are 'found' as the solution as they meet the clients declared requirements. The sustainable design process is undertaken so as to decrease or minimize as much as possible the solution's negative environmental, social and economic impacts. A pictorial representation of this category can be seen in Figure 2.

This category is illustrated by Uma, who describes finding a solution to the client's declared requirements, in this case within a housing development. While efforts are made to decrease the negative environmental, social and economic impacts of the solution, they are still bounded by the clients' declared requirements:

Most of the people we work for aren't interesting in how we do something they're interesting in the outcome and we work as sub consultants a lot and we're told what the out desired outcome is and we're often not included in that process at all, which is incredibly frustrating because we can often see alternative solutions that we see that would be much better um, but for what ever reason they have made up their mind and usually it's because it is the cheapest option. In fact [laughs] it's always because it is the cheapest option and sometimes that cheapest option may actually been a greener solution but it's cheaper for them because they will sell more properties. (p2)

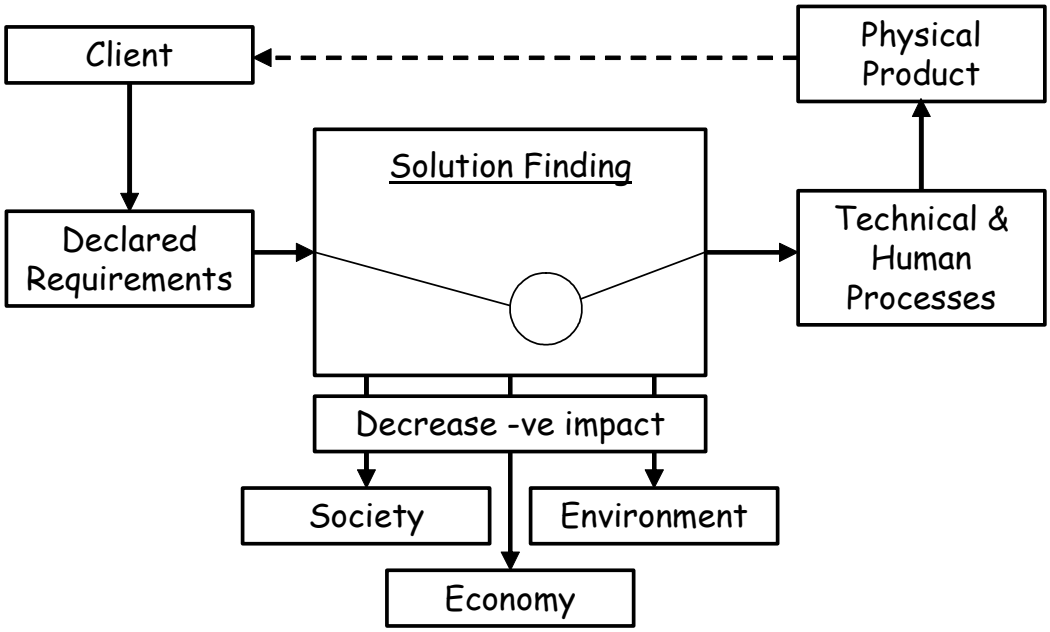

Figure 2: Category 1 - Sustainable Design is Solution Finding (-ve is used to denote negative)

Within this category, there is variation in the form that the solution takes. This is illustrated in Figure 2 where the physical product and the technical and human processes are outcomes of the solution finding process. Both are always present, but one or the other is selected as the focus of the sustainable design process.

Max describes the solution as a product that has to meet the client's declared requirements, in this case of function, aesthetics, safety and cost, while trying to decrease its associated impact. The processes that develop the product are still considered, but the sustainable design activity is focused around the design of the product itself:

Sustainable design to me is the, the production or the manufacture of of products, I'll keep it to products, that meet your, you know, basic requirements of function, aesthetics, safety, cost but also, on top of that and it's part of the whole, it's not something that's added on, is the concern for the environment and the awareness of the environment … which is given just as much weighting as any of the other ones. (p8)

In contrast to Max, Celia focuses on changing the human processes as sustainable design. A final physical product is still developed, in this case a building, but the focus is on changing the processes used to create the product:

Celia: *One of our project managers came from a trade background … if you like on the ground and so he didn't necessarily see any usefulness in any of this [sustainable design]. He could appreciate it but in reality, what the builders do and the tradies do was not necessarily in line with it and it was all given lip talk to, and so it was trying to change his viewpoint, well you know the '[The boss] says' helps because he doesn't have a choice. He needs to ensure that they have this [design] plan filled out, the the [sustainable design] matrix done and everything else and it's also taking new products to them and trying to … get them thinking you know, what it all means and actually look for projects you know, products themselves so I, they'll actually come to me now with new products that they've read or heard about or you know, anything else to be trialled and um, but it's just, it's just the experience of trying to change a mindset that you know, is very much grounded in the operations to think [pause] bigger.*

Researcher: *And how important do you think that is for sustainable design?*

Celia: *Oh extremely important, and I mean they um, you know probably now, whenever we are about to build a new building [pause] we have a big presentation and the the architects, the consultants, the engineers and everyone from the consultancies, they turn up and we'll have the [head] talk about um, you know the building and what we expect of the building from an [organization] perspective, [name of person] will say something. I'll talk about the same building requirements and what we expect of them when it comes to sustainability and then the project manager will talk more about, you know, the actual process of, you know, the design and construct process and all that sort of stuff; whereas that's only happened in the last three months. Sustainability you know, has now taken a front seat. (p5)*

Either focusing on the physical product or the processes that produce the final product, this category is still focused on finding a solution within a given set of declared requirements.

<u>Category 2: Sustainable Design is Reductionist Problem Solving</u>

Sustainable design is the process of identifying and solving a client's problem by making separate decisions that each decrease the associated environmental, social and economic impact. (n=4)

The focus of this category is on the process of solving a client's problem. A final physical product is produced from the associated technical and human processes. In responding to an approach from a client, the sustainable design process identifies and defines the problem to produce a set of requirements for the solution. This problem identification and the subsequent development of requirements are *jointly constructed* by the client and the designer as part of the sustainable design process.

The process is an iterative one, but only one part of the problem identification or solution is considered at any one time. Each iteration of the design process produces an interim design solution, which is used to further define and explore the problem, and subsequently to refine the requirements of the solution. This process is represented by the feedback loop in Figure 3 (labeled Problem Identification), where each solution developed is fed back through the sustainable design process to further develop the solution.

A reductionist approach is taken to solve the problem. In this reductionist way, the problem is reduced to a set of smaller parts and solved independently of each other, without an awareness of how the parts influence each other. Each part is solved trying to help solve the overall problem while minimizing the negative environmental, social and economic impacts from that individual part.

The process of identifying the client's problem rather than just accepting the client's initial requirements is described by Danny:

We undertook I suppose to start, from a very broad point of view looking at what would the market want, what were our goals and and trying to set some specifications for our product … If you try to work from an existing product, like modify a conventional vehicle to try and meet your requirements, essentially … you're starting with a compromise um, and that you would never truly achieve the outcomes you'd desire and in fact often you'd end up going backwards. So clean sheet design was called for, clean sheet in the sense of er let's start from scratch; let's not make any assumptions really at all beyond saying it's a car; it's got four wheels; we've obviously got to meet certain Australian design rules, for example, so that it is actually registrable and saleable, but otherwise let's not make too many assumptions. (p2)

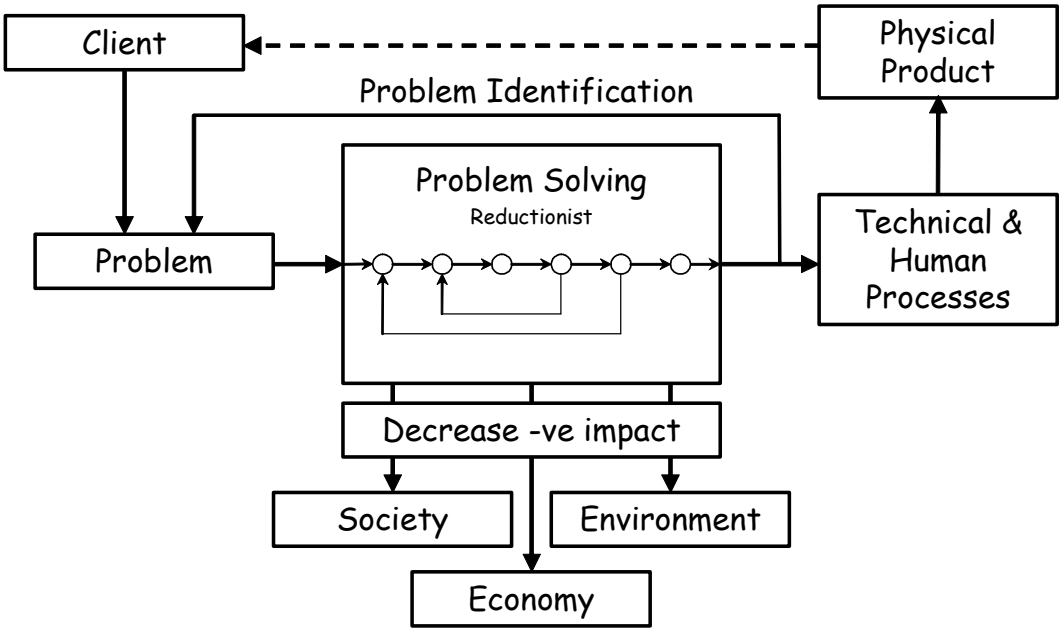

Figure 3: Category 2 - Sustainable Design is Reductionist Problem Solving (-ve is used to denote negative)

In addition to Danny, Zach emphasizes the reductionist way that the elements of the problem are dealt with, where each decision is made to try to decrease its associated impacts independently:

We broke it, the environmental issues down into um, oh, air, water, energy. They use a lot, where should we start, they use a lot of energy for compressed air um, so if it can make the compressors more efficient or simply use less compressed air. Often you can replace compressed air with non-

compressed air if you're just blowing things, for example um, because they use a lot of compressed air to clean things after they've worked on them. They use energy in welding for aluminum boat building so welding equipment often is oversized. If it's old it just uses a lot of electricity so just replacing is a good thing to do. Then there's the standard office type things - lighting, air-conditioning. Manufacturers, fiberglass boat builders would use resins so they they might have heating and things like that so making that more more efficient. (p3)

Category 3: Sustainable Design is Holistic Problem Solving

Sustainable design is the process of identifying and solving a client's problem holistically on a systems level, to increase the environmental, social and economic value of the solution. (n=2)

The focus in this category is on the process of identifying and solving a client's problem *holistically* on a systems level. A final solution, in the form of a physical product and associated technical and human processes is produced to address the client's problem. A diagrammatic representation of this category is presented in Figure 4.

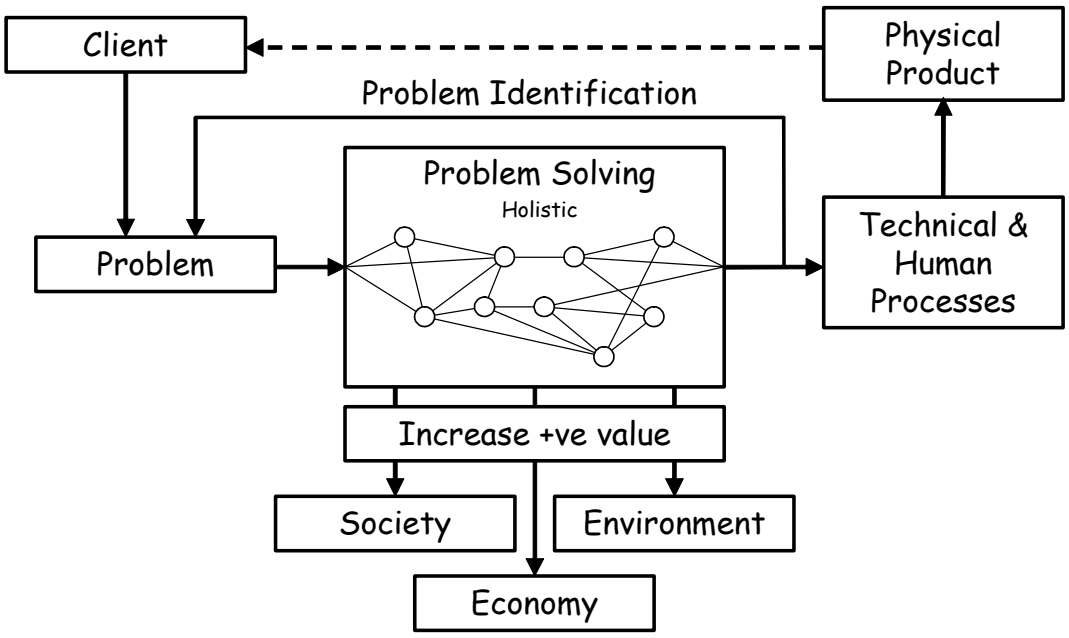

Figure 4: Category 3 - Sustainable Design is System Problem Solving (+ve is used to denote positive)

The holistic nature of the process is such that the client's whole problem is considered at all times, and not as a set of parts that are solved independently. The identification and solving of the problem are conducted concurrently with each other and with an understanding of how one influences the other. In solving the client's problem, each decision is made with an awareness of how that decision influences the other elements of the system. By taking a holistic approach, the solving of the client's problem is focused on trying to increase the environmental, social and economic value of the solution to the client, by considering all the decisions that are made together. Individual impacts are not considered in isolation, so the idea of value is used instead for the whole system. Accepting an alternative solution in one part of the system that has a

greater negative environmental impact than other alternatives may enable the whole system to have less of an environmental impact overall.

The holistic nature of this category is discussed by Walter, who talks about challenging conventional mining operations by taking a holistic view of the client's problem:

There's been a project run by one of the [organization] centers which is mine to mill, which is taking a more systems approach to a mining operation. What's tended to happen is the mine has tended to optimize its own sort of things from an economic basis and then the mill has tended to do its own thing and if you get them to talk to each other and focusing on energy in particular, what, people have concluded is that generally speaking it's more effective to use more explosive in the mine, break up rocks more finely and then consume less electrical energy in the mill in crusher cranes. All the studies they've done have tended to support that and all the studies they've done have tended to be done on the basis of economics - what's the best thing for us financially. But they have made the argument that environmentally, because we're consuming less power, it's better, but what people have not thought about is well if you're using more explosives, okay, we're using less electrical power but we're actually using more explosives. What are the environmental impacts that come with those additional explosives. How energy intensive is er, the manufacture of a ton of ammonium nitrate and therefore is that claim that we're doing the right thing environmentally really right. It might not be; it might actually be worse. (p16)

By looking at the problem of crushing the mined rock in a holistic way, the conventional thinking of using more explosives is called into question. Walter argues that this may in fact have a greater negative environmental impact, and that by looking at the system holistically, a greater positive environmental and economic value could be obtained.

Category 4: Sustainable Design is Social Network Problem Solving

Sustainable design is the process of identifying and solving a client's problem, embedded within a wider societal context to increase the environmental, social and economic value of the solution to both the client and society. (n=5)

The focus of this category is the framing of the client's problem within the larger network of problems facing society. A solution is developed by considering the client's problem as being embedded in a wider social context of problems. Considering this wider context brings with it a set of requirements and constraints that are included in the problem solving process as well. The intermediate outcomes of the problem solving process are fed back into further defining the problem. This may in turn reveal a different set of problems facing society than originally thought, which are then fed into the sustainable design process.

The identification and solving of the client's problem framed within the network of social problems is carried out holistically on a systems level. For each decision taken there is an awareness of how that decision influences the other elements of the system. How each decision that is taken affects the wider set of problems facing society is also recognized and is included in the decision making process. A diagram of this category can be seen in Figure 5.

The solution that is produced is done so to increase the positive environmental, social and economic value of the solution within both the smaller problem for the client and wider network of problems for society. The solution is still for the client, but is also developed to address the problems facing society that have been identified during the sustainable design process.

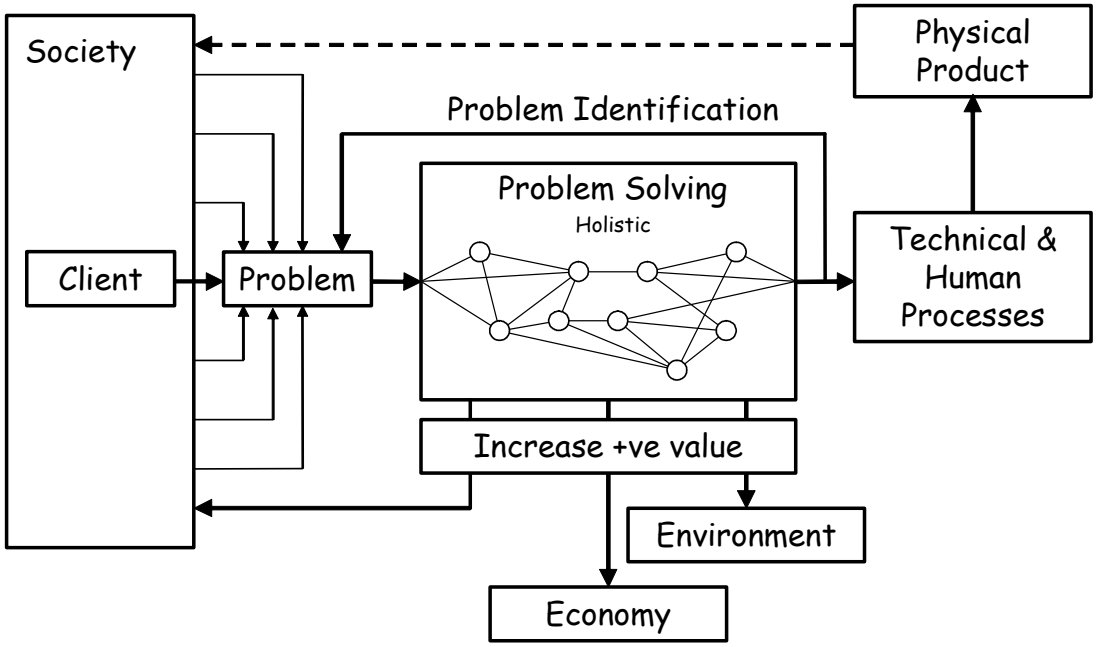

Figure 5: Category 4 - Sustainable Design is Social Network Problem Solving (+ve is used to denote positive)

The focus of this category as solving problems that are part of larger problems facing society is illustrated by Larry specifically in terms of water:

In terms of assessing whether an engineer understood and can practice, in a way that understands that what they're doing will change the way communities work, and in the past engineers have never done that, they've never asked the community whether they really want curbing and guttering, it's just a nice engineering practice to do it. Um, but of course a lot of people now are saying you know, "why do we collect all the water on the roads, and we put it all down the stormwater and shove it away, when we're such such a desperately dry continent?" You know, and that was a neat thing for engineers to do. If you go back and look at drains, stormwater drains designed in the late Forties, Fifties, Sixties, they're all concrete lined, very efficient. You know the, hydraulics is beautiful. But of course, we just losing all the water, 'get it out of here fast' [laugh] was the concept, um, where as now we put barriers and wetlands and retention basins, swales, and all these things … I think it's fairly critical to um, to get an acceptance by the community of the projects and why you doing them and to listen to concerns, as I say um, this is another example. I'm picking up [a] water bottle. [long pause] Did engineers ever ask the community if they wanted potable water piped to their house? No, it was a good engineering solution. Now people are running around, spending four or five dollars a liter to buy potable water and hosing their garden and washing their car with potable water, which is ridiculous. (p4)

Larry goes on to emphasize the focus of this category on solving problems that are part of larger problems facing society, and the need to understand how the designs that are created impact the wider society:

I went through my four years of undergraduate training and, and design to me was just here's the problem, and you sit down and solve something. Whereas design is much more than that. It's [pause] systems thinking. It's bringing a whole lot of inputs to analyzing [the problem]. [Pause] But then sustainable design takes it that step further and introduces to my mind the concept of a human issue … and a environmental issue. See it's [long pause] true triple bottom line applied to design and that's sustainable design. [Pause] And I think you must first have a basis in the philosophy of design and how design impacts on both you and the society that you designing for. (p15)

Category 5: Sustainable Design is a Way of Life

Sustainable design is a way of approaching life where all the activities engaged in aim to increase the environmental, social and economic value of the outcome to both the individual and society. (n=6)

The focus of this category is on sustainable design as a way of life that pervades all or most of the decisions the designer makes. In particular, sustainable design acts as a guiding belief or ethos for the way designers approach a broad range of aspects of their lives. There is no separation between the work done as a professional designer or as a person; they do not leave their personal beliefs at the door of the office in the morning. The core process of sustainable design is trying to facilitate this way of life.

The design problems to be solved may be provided by an external client or by the designer herself. There is a realization, though, that not all of the problems faced can be solved to the level that is either required or wanted. This being the case, the designer attempts to increase the positive environmental, social and economic value of the solution as much as possible, for the client as well as for the wider society. A diagram of this category is presented in Figure 6.

The focus on sustainable design as a way of life is discussed by Amy, who argues that sustainable design should be treated as an integral part of life, and not separated out as 'practice':

I guess I don't like to just think of it as sustainable design. To me it's just it's part of life. It's not a separate thing that I can single out. That's how I like to think of it. I think a lot of how [pause] we're required to work, makes it into a separate thing, gives it a star rating, puts it in a category where it has to be judged, it has to be measured, it has to be costed, when it should just be an integral part, an indistinguishable part of life [long pause] if we're going to survive. (p9)

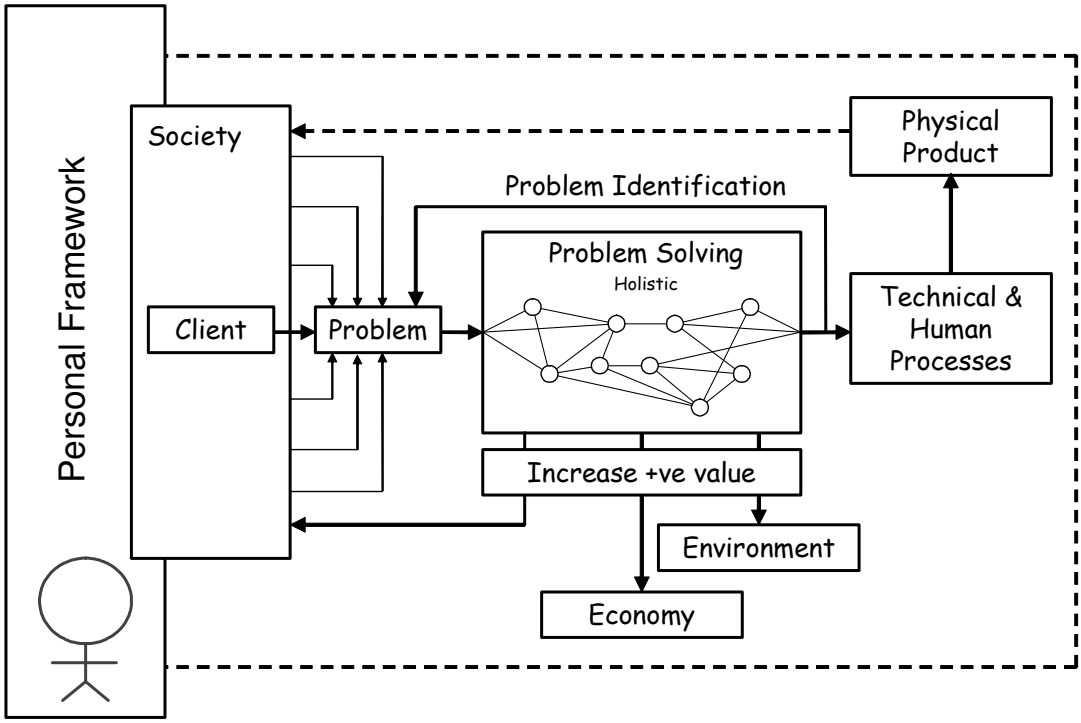

Figure 6: Category 5 - Sustainable Design is a Way of Life (+ve is used to denote posotive)

Henry takes this point further, and tells of how he encourages others he works with to use sustainable design in their professional and personal lives:

I'm trying to show people that by taking on sustainability at work and at home, they can take control over global warming. [Pause] Hence I say 'Take sustainability into designs and change your designs, [then] take sustainability in design home. Pull out your ordinary light bulbs, put in compact fluorescents, put a bucket under your washing machine discharge and carry the water into the backyard. Open your doors and windows at night to cool down your home. Um, all those sorts of things, compost your food scraps. When you're designing at work [pause] look at the whole system. How can you optimize the the whole system [to] come up with better solutions?' I give people hope [pause] by basically saying 'Your children ultimately will inherit a better Earth.' (p15)

By using sustainable design as a framework for both professional and personal activities, sustainable design moves from just a process and becomes a way of approaching life.

Relationships Between Categories of Description

The relationships between the categories of description is in the form of a hierarchy, from less comprehensive to more comprehensive in terms of both the aspects the categories include and the linkages between these aspects. This hierarchy can be seen in Figure 7, presenting both similarities and variations between the categories of description of sustainable design.

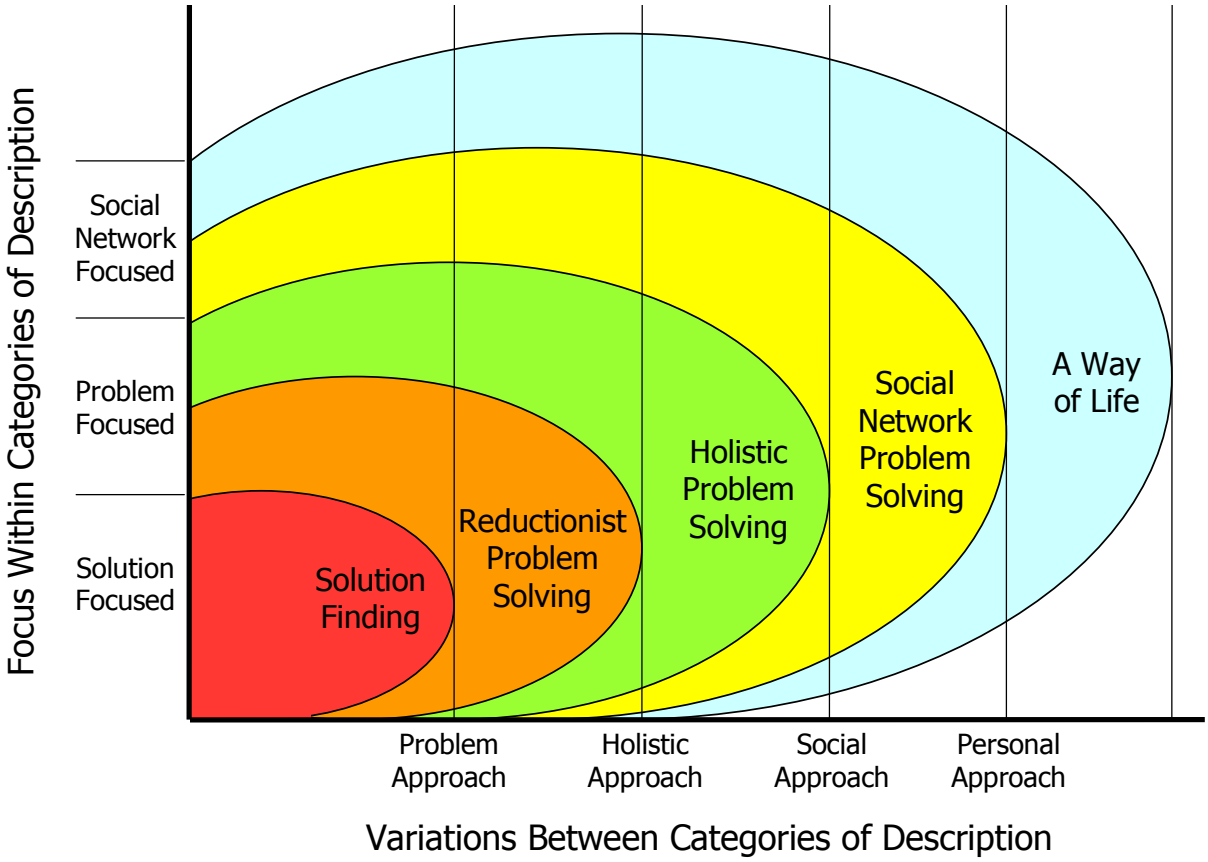

Figure 7: Relationships between Categories of Description

There are three different focuses within the five categories; solution focused categories, problem focused categories and social network focused categories. The focus within the category broadens as the categories become more comprehensive, which effectively increases the scope of the solution. The solution focused category is just looking for the solution within the client's declared requirements. A solution is found solely to fit with the requirements, as that is all that matters to the designer. The problem focused categories reconsider the client's problem in collaboration with the client, and jointly determining the final requirements of the solution. This enables other possible solutions to be proposed that may not have been allowable within the initial client's requirements. The social network focused categories look not just at the client's problem, but at the network of problems facing society that surround and influence the client's problem. The solutions that are found are done so within this broader framework.

The approach the designer takes is the main variation between the five categories of description involve. The approach the designer takes enables them to have a different focus within the category. The four different approaches that distinguish the different categories are a problem approach, a holistic approach, a social approach, and a personal approach. The problem approach echoes the change to looking at the problem from finding a solution. The holistic approach is a move from making design decisions in a reductionist way to making them in a holistic way, with the focus still on the problem. The social approach involves the move from looking just at the

client's problem to looking at the client's problem within the larger network of social problems. Finally, the personal approach is the move from considering sustainable design problems externally, to seeing them on a personal level with the designer as a part of society. This results in sustainable design being seen as a way of life, as opposed to a way of designing, which is what the four previous categories refer to.

The specific relationships between the five categories of description in hierarchical order are as follows.

Category 1 → Category 2

Category 1 has a focus on producing a solution to a client's declared requirements, as already identified and determined by the client. The key variation between this category and category 2 is the move from accepting these declared requirements as is, to identifying, along with the client, what the requirements are from the client's problem. This identification process is one that involves both the client and the designer in jointly constructing the final set of requirements as the problem is explored and from the interim solutions that are produced. Starting with the problem enables the designer to develop different requirements than the client may offer. Using these may deliver a better solution overall to the client, or reduce the negative environmental, social or economic impacts of the solution *compared to if the original client's requirements were used*. Category 2 is thus more inclusive, as a solution is still found but to meet jointly constructed requirements.

The variation between categories 1 and 2, from solution to problem, is demonstrated by the following quote from Uma. While she explains having to work within the client's declared requirements, she can see that collaborating with the client to determine what their problem is and designing a solution from that would have achieved a better solution. In this case, Uma relates an experience she had with the designs of a housing development:

[The housing plan is] submitted to council and council either approves the plan er, in which case [the client] is required to implement whatever they've said they will do in the plan. Or it's rejected on the basis of they haven't done enough, they haven't demonstrated that they are really trying to make sure they are not having a big impact on the water ways. In which case it comes back to us and we sort of look at it and go aw geez this is hard because usually [the client] comes to us and they've done the lot layout, they've decided exactly what they want. There might not be a square inch of space for us to do anything and they say fix it, you know, we want to get this passed. Whereas if they approached us before hand, we could actually work with them, and it might mean that they lose half a lot, but the there is a mentality there that needs to change. (p3)

By jointly identifying the problem, they may have had a much better outcome with less of an environmental impact. Instead the solution that was found within the declared requirements was not as good as it could have been.

Category 2 → Category 3

Category 2 and 3 both focus on the problem as the core of sustainable design. The key variation between the categories is how this problem is handled. Category 2, reductionist problem solving, looks at the solving of the problem as a series of smaller parts, where one is solved after another. Each part of the problem is solved separately without reference to the influences the parts have

on each other, to decrease the environmental, social and economic impacts of each part. Category 3 looks at the problem solving process holistically, where the problem cannot be solved by reducing it into separate parts and solving them independently. As a result, the problem must be solved holistically as a whole system, with an understanding of how the consequences of each decision impact the other elements of the system. Category 3 is more inclusive than category 2 in the way that it approaches the problem solving process and is thus higher in the hierarchy.

This holistic approach also carries with it another variation between the two categories; the move from trying to decrease the negative impacts associated with the product, to trying to increase the positive environmental, social and economic value of the product. Minimizing negative impacts can be straightforward when making single decisions, as one option usually has less of an impact than others. Trying to minimize the impacts associated with multiple decisions that have an impact on each other at the same time becomes a more complicated problem. Making a particular decision may minimize that decision's associated negative environmental impacts, but may impact other elements in an unforeseen way, increasing the negative social impact in another part of the system. In category 3, the aim is to increase the overall positive value from all the decisions made. With this approach, a larger negative environmental impact may be acceptable in a certain part, because it would mean that overall, the positive environmental value of the system is greater.

As an illustration of this trade off aspect of category 3, Walter discussed part of a mining operation as holistic problem solving, where decisions need to be made with an understanding of how all the elements impact each other in order to increase the value of the whole system. In this case, a student in a class Walter is teaching proposes having a larger negative economic impact than is the norm, in order to have a greater positive social value overall:

It's always that question with mines, how long they're going. And when they close there's a number of very serious issues they're going to have to face up to about the local communities and health facilities and all those things. … One of the questions that a student asked, that this particular student had was [pause] have they ever considered actually slowing down production, so only mine at half the rate and make it go longer and give yourself more time to adjust and [aim for] some of those sustainable outcomes.

And if you think about that in terms of the broader mining industry um, it's actually quite a good question. When we've got an ore-body, what are the factors we consider when we consider the production rate and how long are we going to exploit that for um, in terms of the social impacts? Now if it's in the middle of nowhere, because many mines in Australia are, and you haven't got a local community, then it may not be an issue. But if you try to do something with some regional outcomes, then instead of going in there for ten or twelve years, which is quite a common mine life for a small goldmine these days, is there an option to do it more slowly. That flies in the face of all the engineering thinking, which is all about economies of scale and doing things more quickly, and everyone's talking about expansions, because on the financial scale that's a better outcome. (p15)

<u>Category 3 → Category 4</u>

The variation between category 3, Holistic Problem Solving and category 4, Social Network Problem Solving, is the move from just looking at a client's problem to looking at a client's

problem as part of a network of wider problems facing society. In category 3 there is not an awareness of the larger dimensions outside of a client's problem, but it is still solved holistically to increase the positive value to society. Category 4 includes the greater awareness that a client's problem is a subset of a larger network of societal problems, and tries to solve it to increase the solution's positive value to both the client as well as the wider society. Category 4 is therefore more inclusive than category 3 in terms of the range of problems that are considered.

The following two quotes illustrate the difference between category 3 and category 4. As an example of category 3, Walter discussed a problem the client had with material usage in a process with a focus on the client's problem only, particularly the issue of waste. Waste though is a problem that the wider society is facing also, but these problems are not included in the consideration of the client's problem.

Walter: *We had a theme on general materials use, so just their inputs in terms of what materials were they bringing on site [cough], how efficiently they were using them, what sort of yield they might be getting or how much of that particular product might be wasted um, including the products they were producing. They had a bit of an issue with ammonium nitrate dust and how that was managed at the end of their process, so getting spilt.*

Researcher: *And why do you think that um, why was that important?*

Walter: *Well it, it's important for the company if you're talking about a product, the more they can get into the final product and not damaged or thrown away then obviously financially they're better off then. It also means that the associated um, impacts associated with producing more tone of that product, not only do you get more money for producing a tone but you also reduce them as impacts, incrementally, but still reducing. (p6)*

Simon, on the other hand, discussed the problem of supplying water to households but saw it as part of a larger network of problems facing the wider society, namely the alienation from what is involved in delivering everyday services such as water in the middle of a drought, and the impact that has on the environment, as an example of category 4:

When you take water from the tap, um, most people don't know where it comes from, but it's rained somewhere, and it's been gathered in a dam, its flowed in a stream, its come to a place, its been treated, its gone through pipes, and its come out of a tap somewhere. Um, there's a whole pile of things happened. So my sense of alienation er, is is about um the overwhelming majority of people, including the leaders of the country, the leaders of our societies, not understanding or knowing or thinking about what's involved in the life that we lead. So we focus on topical, sometimes trivial um, often passing fads, fashions er, issues they call them, you know what's the issue or issues, the issue itself is a construction. [pause] And at the moment the the very fact that, you know, we have a water er, scarcity here in South-East Queensland, um, people are responsive to water restrictions, um, but most probably haven't thought about why we are in those water restrictions. It's largely explained in terms of drought, but [pause] as equally important as the drought is the the wanton waste of the resource and the way we use it. There could be a lot more water in that dam right at this moment had this, had this community not wasted as much as it has in the past five years, when the dam was last full. (p10)

Category 4 → Category 5

The key variation between category 4, Social Network Problem Solving and category 5, A Way of Life, is the change from seeing sustainable design as something that is done as a designer, to something that is done as a person for the greater good of society. Moreover, sustainable design becomes a framework for approaching aspects of life. Category 5 is thus more inclusive than category 4, as it incorporates sustainable design in a professional context as well as a personal context.

In category 5, there is no separation between what is done as a designer and what is done as a person, as Natalie describes:

For me, I do try to integrate, keep that integrated, that my personal life and my um, professional life are actually one and the same. Like I am one person, I am not two, you know, like a working person and a private person and so I try to keep that sort of integrity across er, across both of them. (p4)

This is contrasted by Simon as an illustration of category 4, in not seeing sustainable design as a way of life. He is happy to apply sustainable design principles in his work, but will still buy products for his personal life that he knows and admits have negative environmental and social impacts, in this case his leather lounge:

I use the example in fact of my er nine hundred and ninety-nine dollar, five seater leather lounge at home that we bought a couple of weeks ago. Um it's nine hundred and ninety-nine dollars to me because um the Chinese do not protect their environment, I can safely assume that the um er harmful materials used in the treatment of the leather to make the thing were not internalized but now probably now in the Yangtze, um and that the Chinese laborers who were enjoying by Chinese standards probably six dollars a day or whatever to, to make the thing are relatively well, by third world standards, well employed but by our standards of course um they provided me a subsidy because I don't, I get a lot more than six dollars an hour. So if you're going to look at sustainable design, you you've got to look well beyond the engineering implications [pause] and think about it in that in that context. p7

The five categories of description and the relationships between them form the basis of the results of this research. Before the implications of these qualitatively different experiences of sustainable design can be discussed, it is worthwhile looking at the distribution of individuals across the five categories identified.

Implications for the Practice and Education of Sustainable Design

The research presented in this paper enhances the current understanding of engineering practice, as well as highlighting possible improvements to the education of students about sustainable design. It does this by highlighting an aspect of practice previously ignored in engineering. This aspect, the ways practitioners *experience the practice* of sustainable design, has implications for the current practice of sustainable design. It calls into question the traditional view of competent practice being constituted by specific attributes, in line with what Sandberg[7] argues. Further, more comprehensive ways of experiencing sustainable design, it is argued, will help designers to

address the challenges they will face in the future. These implications also translate to the education of engineers about sustainable design, as the focus of engineering education is on creating competent professionals. There are three levels for which this research has implications for engineering practice and hence education, on an individual, design team and organizational level.

Individual Practice Level

The categories of description have many implications for individual practitioners. In particular, the ways that practitioners experience sustainable design have been described in terms of how they act in practice, and what they regard as sustainable design within their work. A similar study was conducted examining the experiences of engine optimizers at Volvo[7]. It found three different ways that workers had experienced engine optimization: optimizing separate qualities; optimizing interacting qualities; and optimizing from the customers' perspective. The first two of these categories match well with categories 2 and 3 identified in this study, those of reductionist and holistic problem solving respectively. Like the Volvo study, in this research practitioners' ways of experiencing is interrelated to their way of acting in practice.

The subjects were asked in the interviews if there was one experience that changed their understanding of sustainable design. Not many practitioners could single one particular experience out. Instead many described it as a gradual change over time. Thus it could be argued that the development of their way of experiencing sustainable design was more a process of refining their existing understandings of practice, rather than there being a sudden transformation to a more complex way of viewing practice. This agrees with what Dall'Alba and Sandberg[8] argue in their critique of stage models of professional practice. This also has implications for further understanding practice and in particular for the education of students. One important implication for education is that experiences need to be provided to students throughout the curriculum to gradually develop their way of experiencing practice. If practitioners do not change through one particular experience, it is unlikely that students will change due to one particular course.

The relationships between the categories of description have many implications for improving the practice of sustainable design as follows:

Category 1 → Category 2

The relationship between seeing sustainable design as finding a solution as opposed to solving a problem is an important one for improving the practice of sustainable design. There is a key difference between these ideas. In finding a solution to a set of declared requirements, the requirements act as 'pegs in the sand', by defining a boundary within which the solution can be located. The solution is then found within this limited space (see Figure 8). Solving the client's problem however involves the evolving development of the requirements boundary, in collaboration with the client. While the client's idea of the problem may start small, the evolution process allows the designer to explore possible solution spaces that would not be allowed in solution finding. This also points to the need in education for students to be given design problems, rather than specific design tasks. Further, these problems should be able to be explored and solved through a variety of pathways.

Another interesting implication of the first two categories of description identified is that they both could be thought of as 'good' traditional design. It is argued that Category 1 can be thought of as traditional design, with the addition of 'decreasing the environmental and social impacts'. In traditional design, a client has a set of declared requirements, and a solution is found, in the form of a product and processes, that decreases the associated costs. Category 2 can be thought of as 'insert traditional design process here' in the problem solving box, as most traditional engineering design tends to be reductionist in nature (see Figure 3).

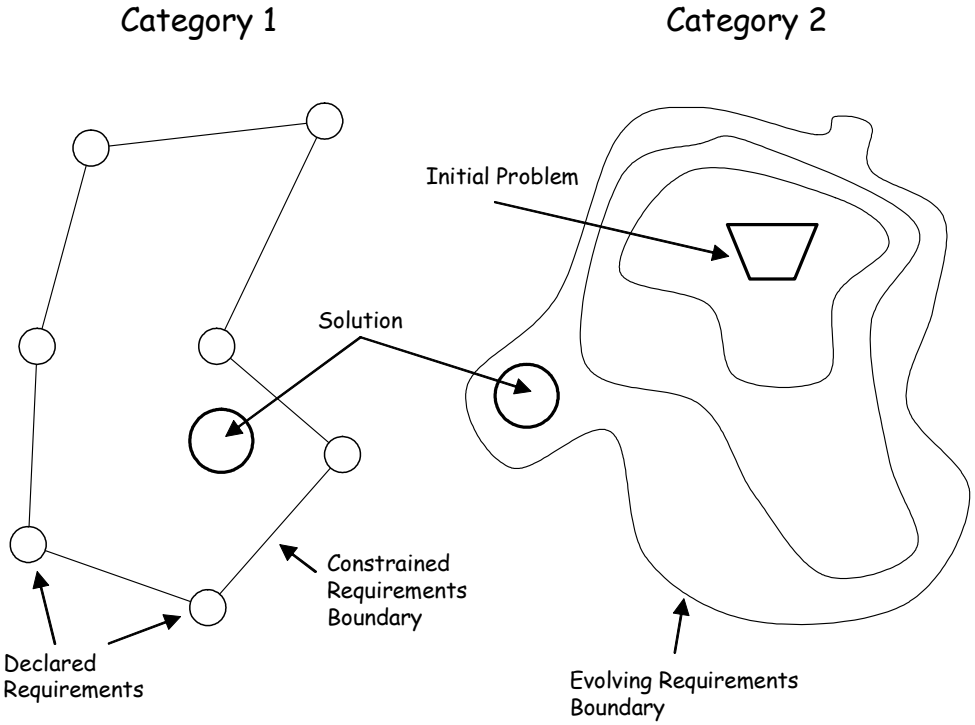

Figure 8: Comparison of Solution Finding and Problem Solving

Category 2 → Category 3

The major implication of the relationship between Category 2 and Category 3 is the focus on the co-evolution of problem and solution spaces. In both categories, these are developed together, as this helps in exploring the problem solving space seen in Figure 8[9, 10]. It also allows for more creative designs to be pursued. Traditional systems engineering however, used for large complex designs, is not flexible enough to cope with this co-development, even when it is tailored[11, 12]. This suggests the need for a holistic problem solving approach, looking at the interconnections between elements of a design (Category 3). Another interesting aspect of this relationship between Category 2 and 3 is the change from minimizing negative impacts to increasing positive value. Once a holistic view is adopted, individual decisions are no longer easy to make. In a holistic sense, a decision to lower the negative environmental impact of an element of the design may, for example, increase the negative social impact on another part of the system. Thus the shift in Category 3 to looking at the overarching positive value of the design. Holistic problem solving is also linked to the idea of service and flow from Natural Capitalism[13] and the human

vitality principle[2]. Taking a holistic approach to solving problems allows for the shift to a service and flow economy.

These issues also have implications for the education of engineers about sustainable design. It is important to provide students with problems that are complex, that have to be solved in a holistic way. While generally these are harder problems to not only set but assess, sustainable design embodies the need for a holistic perspective.

Category 3 → Category 4
The relationships between Category 3 and 4 point to the need to focus on the wider social and environmental problems surrounding the client's problem. Even though Category 4 only included the larger societal context, it is argued that the environmental context also needs to be made explicit. This relationship also demonstrates the need to look at the impacts of any proposed solution to the environment and society, closing the feedback loop shown in Figure 5. Category 4 can also be seen as incorporating the waste equals food concept from the seven generations principle[2]. For this to happen effectively, it is argued that operating at least at category 4 is essential. Not only is a holistic view required to look outside the confines of a particular company or system, but there needs to be an awareness of the issues within a wider social and environmental context to understand how the wastes from one system can become food for another system. An example of this is the Kwinana Industries Council[14], which is incorporating the idea of By-Product Synergy, or waste equals food, to an entire industrial area. Local industries have come together and identified the inputs (food) and waste outputs from their systems and tried to see where the wastes from one industry can be used as a food for another industry.

This also implies that the problems provided to students to learn about sustainable design need to have this wider social awareness embedded in them. One possibility to do this could be to embed local community issues into design problems that the students tackle.

Category 4 → Category 5
The main implication of the relationship between Categories 4 and 5 is that for some, sustainable design is something they do as a professional, whereas for others, it is a way of life. Ultimately many of the principles of sustainability and sustainable design suggest that Category 5 is the ultimate approach, and the one that needs to be adopted to have a sustainable future. As to whether or not students should be encouraged to see sustainable design as a way of life is left for another time.

<u>Design Team Level</u>
At a design team level, the major implication of this study is the realization that different designers and the other stakeholders involved will have different ways of experiencing sustainable design. These will influence the thoughts and actions of individuals within the group. This being the case, when working in a group situation on sustainable design, it is important to firstly try to identify what the different group members' ways of experiencing sustainable design are. This will help address the disagreements which often arise due to peoples' different understandings of the same situation[15]. It must be remembered however that everyone operates or performs tasks at different categories depending on the situation. This also has implications for

students, particular working in design teams. Students need to be made aware of both their way of experiencing sustainable design is, as well as their fellow team members.

Organizational Level

Any workplace wanting to integrate sustainable design into their organization should encourage practitioners to critically reflect on their current practice, and how integrating sustainable design into their work can develop their way of experiencing that practice[8]. A necessary feature of enhancing practitioners' ways of experiencing practice through reflection is enabling them to become aware of their current ways of experiencing. Further, they need to be made aware of other ways of experiencing practice that exist. It is easier for change to take place if practitioners are aware of both where they are and where they could be in their experiencing of sustainable design.

Different people in a company will have different ways of experiencing sustainable design. The same issues that apply to a design team apply to a whole organization. People in the organization need to be aware that others may have a different way of experiencing sustainable design that will inform the way they act in practice. This knowledge can be used by people with more comprehensive ways of experiencing to constantly challenge others to transform their ways of experiencing sustainable design. More generally in an organization, "there is scope for critically reflecting on the function of the organization or the service it provides in a way that calls into question, and extends, experiencing of practice"[8](p404).

Further, it is argued that an organization as a whole develops, in effect, its own 'way of experiencing' sustainable design when compared to other organizations. It does this through the internal practices it uses, the culture and values it instills in its staff, the experiences of the staff that work for it, and the projects it chooses to work on. Different organizations act differently when confronted with sustainable design issues, hinting that these different ways of experiencing sustainable design at an organizational level may exist, though this is yet to be investigated.

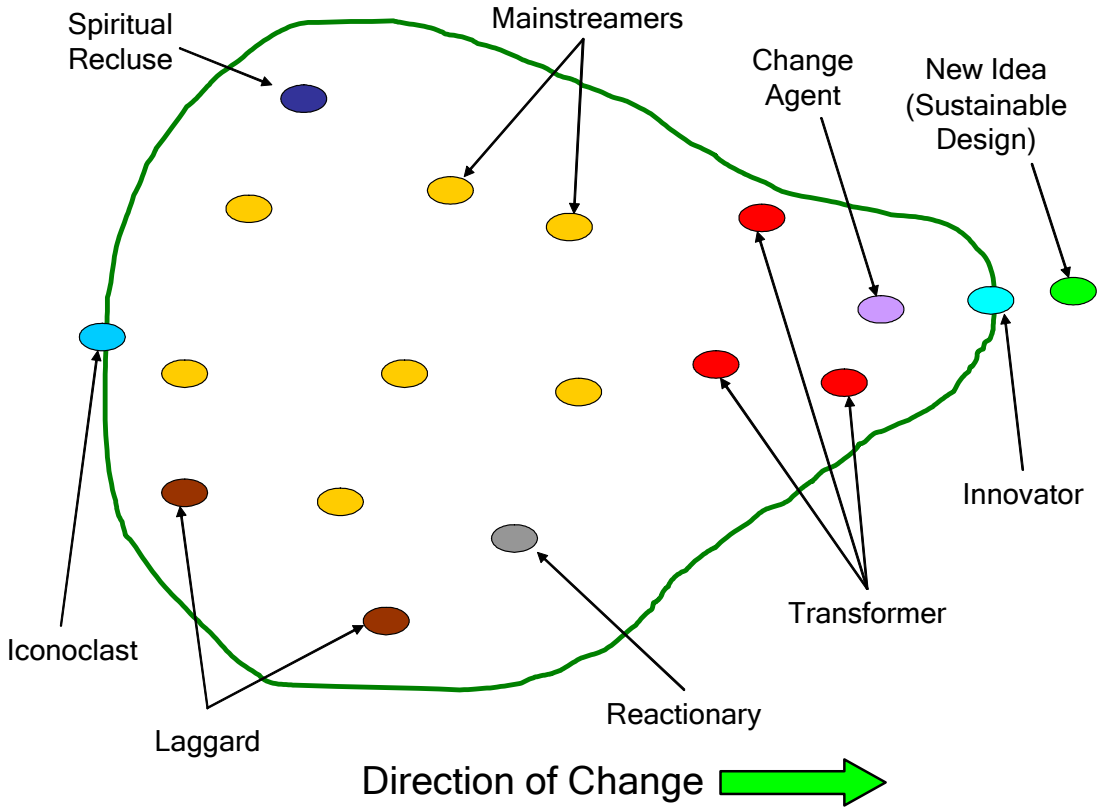

Figure 9: Amoeba Model of Cultural Change

This research also has implications for organization change toward more sustainable practices. As McLennan[2] argues:

Organizational change from a conventional company to a green company or institution requires changing the mindsets and patterns of numerous people, all at different points in their overall journey and at different levels of interest in sustainable design.

AtKisson proposes an amoeba model for organizational change and innovation diffusion, seen in Figure 9, which is adapted from[16]. As AtKisson[17] proposes:

Picture human culture - or any particular subculture of it - as a giant amoeba. Individuals are like the molecules that make up that amoeba. They move around, playing different roles at different times in different parts of the organism. An amoeba moves by sticking out a small pseudopod ("false foot") into new territory. The rest of the organism inevitably comes sloshing along behind. Because of this sloshing effect, the nucleus or center of the amoeba arrives a bit late on the scene compared to the majority of the organism's molecules.

This review of basic biology provides an elementary model for how cultures change. The sloshing of the nucleus is akin to the phenomenon of the lagging center - the tendency for the mainstream (and especially the power structures) to be far from the forefront of cultural advance. The pseudopod is the realm of the innovator and the change agent. Not every pseudopod rules the

day; in a culture, there may be antagonistic forces trying to push another pseudopod out in the opposite direction. Again, the message for the would-be world-changer (or organization-changer) is clear: the trick is to have a winning pseudopod. But, as in biology, a pseudopod that leads the whole amoeba on to more nourishment and growth opportunities is far better than one that succeeds in leading the whole into the microscopic equivalent of a wasteland.

Within the model, there are many players, each acting to either move the organization toward sustainable design, or resist the move. It is important to note that in reality, everyone plays the roles identified by AtKisson in different contexts. For example, someone may be an Innovator when it comes to new gadgets, a Mainstreamer when it comes to Computer Aided Design packages, and a Reactionary when it comes to multidisciplinarity. There are a few roles of particular interest to changing organizations.

According to the model, all innovations within an organization start with an Innovator, a person or group of people who invent, discover or initiate a new idea. These people are on the boundary of the organization, constantly looking out for new ideas to incorporate into the organization. As these people are on the boundary, they find it hard to diffuse the new innovation they find through the organization. They need Change Agents.

Change Agents are the people that actively promote new ideas through an organization. They are the innovation marketers, those people that sell the new idea to the rest of the organization. "Change Agents understand that convincing people to try something new is more art than science, and depends more on communication skills than (merely) compelling evidence."[16](p182). Change Agents operate between the 'lofty' ideas of the innovators, and the people 'on the ground', focusing on the benefits of the new idea. For an innovation of be adopted and change to happen, the difference in perceived value between the old and new systems needs to be greater than the perceived cost of the change[16]. The idea is similar to Schein's[18] notion that for change to happen, the survival anxiety has to be higher than the learning anxiety. There are three basic strategies for motivating transformation that Change Agents use[16]:

- Promote the new – increase the perceived value of the new system or idea;
- Critique the old – decrease the perceived value of the old by attacking it, either subtly or openly;
- Facilitate the switch – reduce the perceived cost of making a change. This is the most important but often least obvious strategy for change.

The first mainstream people in an organization that change toward the new idea are called Transformers. These people are typically open to new ideas and are the forward thinkers in an organization. They are the group of people that start to shift the Mainstreamers, the majority of people in an organization. The Transformers may change the new idea, making it less radical or easier to use in practice in order to bring the Mainstreamers along[16]. Other people in an organization include Laggards; Mainstreamers who generally don't like change and will generally only change under pressure from the majority of Mainstreamers. Further, Reactionaries are those people that actively resist change, and who have a vested interested in maintaining the 'status quo'. These people change very late, and often only if it is unavoidable. Iconoclasts are the critics of maintaining the status quo, so "while the Innovator pulls the amoeba from in front, the Iconoclast kicks it from behind" [17](p4). Finally, AtKisson identifies the Spiritual Recluses,

who are withdrawn (either actually or metaphorically) from the mainstream, and who are more preoccupied with eternal truths than reality. These people often provide inspiration for the Innovators, Change Agents and the Iconoclasts.

Viewing change in an organization in this way has implications for adopting sustainable design. Firstly, the categories of description identified in this study offer a way of understanding why different people will have different roles for adopting a change to sustainable design within a company. It is argued that those people who are Innovators and Spiritual Recluses most probably experience sustainable design consistent with Category 5, as a way of life. These people are committed to incorporating sustainable design because they believe that it is essential, that it is a way of life. Change Agents and Transformers then may experience sustainable design as Category 4, social network problem solving, or Category 3, holistic problem solving. This will depend whether they are focused just within the organization or consider the wider societal and environmental context. Mainstreamers then are likely to be Category 1 or 2, solution finding or reductionist problem solving. The purpose of the Change Agents and Transformers is to then move the Mainstreamers to more comprehensive ways of experiencing sustainable design. Finally, other groups such as the Reactionaries do not fit within a category identified in this study. All subjects interviewed for this research had experiences with sustainable design and many of them were recognized as leaders in the field. As such, no one discussed experiences that were negative of sustainable design or discussed opposing change. However it is argued that if a study was conducted within a typical engineering company, these negative ways of experiencing sustainable design may become evident.

The other implication for change that this model indicates is that if an organization is committed to moving to incorporating sustainable design, it must encourage the good and remove the bad. That is to say, it must identify the Innovators, the Change Agents and the Transformers and encourage them, while at the same time discouraging the Reactionaries within the organization.

Conclusion

This paper presented the results of a phenomenographic investigation of the experiences of twenty-two sustainable design practitioners. Five ways of experiencing sustainable design were identified and discussed, including the relationships between them. These have many implications for both the practice of sustainable design and hence, for the education of student engineers. The goal of any engineering program is to develop engineers that can practice competently in the workplace. Thus, the implications presented in this paper need to be adopted for students to be able to cope with the complex challenges that await them.

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