AC 2012-5367: THE DEVELOPMENT OF A DFX

Mr. Geoffrey Samuel Frost, University of Toronto

Geoffrey Samuel Frost is a graduate student studying biomedical engineering at the University of Toronto. He completed an undergraduate degree in engineering science at the University of Toronto. He has worked as a Teaching Assistant for the Praxis suite of engineering design courses at the University of Toronto for the past three years.

Mr. Jason A. Foster, University of Toronto

Jason Foster is the Senior Lecturer in engineering design education within the Division of Engineering Science at the University of Toronto. Trained as a Systems Design Engineer and with industry experience in software development and management consulting, he currently teaches engineering design at the cor-ner and capstone levels. His research focus in on scaling innovative engineering pedagogies to suit large classes, and his teaching integrates the theories of Vygotsky, Kolb, Papert, Perry, and Pugh.

Dr. Robert Irish, University of Toronto
Ms. Patricia Kristine Sheridan, University of Toronto

Patricia Kristine Sheridan is a Ph.D. candidate with the Institute for Leadership Education in Engineering at the University of Toronto. She holds a B.A.Sc. and M.A.Sc. in mechanical engineering from the University of Toronto. She is a member of the teaching team and a course developer for the Praxis cornerstone design courses.

Mapping the Development of Design for X

Abstract

This paper uses a historical case study to propose a preliminary, generalized understanding of how DfXs may develop. Engineering design guidelines, also known as Design For X or DfX are used by engineers to better the outcome of their design process with respect to the X in question. For example, Design for Safety is a common DfX, used to ensure an engineer's final output minimizes the occurrence of harm to users. An exploration of how a recently emerged DfX, Design for the Environment (DfE), developed suggests a possible model for the emergence of a DfX.

Historical records for the development of DfE suggest five distinct steps that occurred as the DfE guidelines formed. The steps are described as: (1) A Push, (2) A Brave Step Forward, (3) A Simple Set of Rules, (4) A Recipe for the Implementation, and (5) A Measure of Success. Separate from the core 5 steps, we suggest a sixth outlying step that can occur as the first or last step in the development of a DfX. We have described this step as (6) A Push or Pull. Identifying these stages in the development of DfE suggests that similar stages could apply to understanding or developing other DfXs.

We hypothesize that understanding and generalizing how a DfX emerges has three main values: (1) Identifying emerging DfXs could provide engineering designers with a competitive advantage; (2) Identifying emerging DfXs could allow engineering design researchers to better target their work; and, (3) Engineering educators who focus on engineering design could use this understanding of how a DfX develops to develop class assignments and lecture plans. A historical example of a corporation that recognized, and then adopted, DfE in its early stages highlights the advantages conferred by being aware of DfX formation. We propose that by understanding the developmental stage of a DfX, a design researcher could target their work towards emerging elements within the field. Finally, engineering design educators can leverage this understanding to frame their discussions of design practices and to prompt students to incorporate DfXs at varying stages of development into their design activities.

1 DfX Background

DfX is shorthand for the concept of Design for Excellence[1]. Design for Excellence is an umbrella term that describes a group of engineering design tools. DfXs generally comprise guidelines in various forms that engineers may use to better the outcome of their design process with respect to the X in question. For example, Design for Safety, or DfS, is a common DfX that outlines a process for ensuring a final design minimizes harm to the user and other relevant stakeholders. When a DfX is implemented effectively the results can be hugely positive[2]. There are many different X that have been developed into full DfX literatures, including[3]:

1. *Design for the Environment (DfE)* Design the product to have minimal environmental impact
2. *Design for Safety and Liability Prevention (DfSL)* Design a product so that misuse causing harm to the user or nearby infrastructure rarely occurs

3. *Design for Manufacturability (DfM)* Design the product so that integration into an existing manufacturing facility is trivial
4. *Design for Assembly (DfA)* Design the product so that it may be easily assembled with minimal errors
5. *Design for Reliability (DfR)* Design the product so that a loss of functionality or failure rarely occurs
6. *Design for Compliance (DfC)* Design a product so that compliance with regulatory authorities is trivial

2 The Value of Identifying and Leveraging a DfX

Identifying and leveraging a DfX has three possible benefits. First, identifying a DfX that best serves a given sector and corporation can be invaluable to an engineering designer or design firm. The appropriate application of said DfX can provide a competitive edge to the firm while providing benefits to both the consumer and society[2]. Kimberly-Clark (K-C) is one firm that has benefitted from implementing DfE. In the mind of Ken Strassner, Vice President for Global Environmental, Safety, Regulatory, and Scientific Affairs[4]:

"Design for the Environment will continue to be an important area of activity for Kimberly-Clark because it can be a point of differentiation for us and can help deliver value for our business ... We believe this process will result in reduced costs, increased revenues, reduced risks, and increased brand equity and will position the company as an industry leader."

The ability to quickly identify and implement an emerging DfX trend can be crucial to securing a competitive advantage. In today's constrained economies, any advantage will be essential to succeeding where rivals fail[5]. Correctly identifying and characterizing the developmental progress of an emerging DfX can allow industry leaders to determine the appropriate next steps in the implementation of said DfX. If development is in the nascent stage, the risks of implementation may outweigh the benefits; if in the mature stage, it is imperative that the given engineering firm adopt the DfX as soon as possible or risk becoming uncompetitive.

Identifying an emerging DfX and its stage of development may also be helpful to the academic realm. Identifying the stage of development that a nascent DfX is currently in can suggest to a design researcher that they explore how to "push" the guideline into the next sensible stage, ideally based on historical precedent or on a general understanding of DfX development. Furthermore, recent research in the field of Engineering Design theory has advocated for a Top Down approach to the development of a DfX system that incorporates multiple DfXs into a single omnipotent process[5]. Yet, the literature currently lacks a convincing overview of how a singular DfX develops. Prior to embarking on a project to redesign the way DfXs are developed, we must first understand how DfXs are currently being developed. This understanding may allow future researchers to suggest specific improvements to the DfX developmental pathway so that the top-down approach advocated by some can be successfully implemented.

Finally, we hypothesize that engineering design educators can implement the concept of DfX development levels to make their classroom instruction more effective. Specifically, the concept of problem definition is an important concept for engineering design educators to teach. In a simple form, problem definition requires an engineer to discern: (a) what the problem is, (b) what the engineer plans on doing to resolve the problem, and (c) what processes the engineer plans on implementing to solve their problem. DfXs are essentially well defined common engineering problems that an engineer will encounter when working in a specific field. For example, DfE highlights what things an engineer must consider when designing in the field of environmentally conscious design. The different stages of a DfX's development therefore mirror the depth to which engineers have considered, or defined, a given problem. We hypothesize that a step-by-step descent through the stages of a DfX's development would both motivate students by exposing them to the history of their discipline, and sensitize them to design practices both in industry and in research.

3 Research Methods

The information used to draw conclusions in this paper was drawn from an analysis of Design for the Environment texts. Specifically, the authors began by investigating the most recent publications in the field and looked at what those publications referenced when developing their arguments. This led us back what we believe to be the original cases of Design for the Environment in the large corporate setting. The analysis was biased towards individual authors in the field based on the method used to discover earlier publications.

4 Steps to a Developing DfX

This section outlines a proposed set of generic steps followed by a DfX as it develops. These steps were determined by an analysis of the historical precedent of Design for the Environment, DfE, which is presented in Section 5.

Step 1: Catalyst for Change - A Push

The development of a DfX must begin with a compelling force that pushes for the development of a new technology. This is a common theme throughout human history. The space race, after all, was a drive to prove American superiority over the former Soviet Union. The result was several important technological breakthroughs from rocketry to satellites[6]. The Incan empire, as another example, needed to develop a method of communication for their large empire. It resulted in the novel chaski runner system, a technological breakthrough in organization for a society that lacked the technology of the wheel[7].

Step 2: Isolated Cases and Examples - A Brave Step Forward

As with any new idea or concept, a first attempt must be made. Typically the first few examples and cases form the basis of the emerging DfX. All future research work on the DfX will invariably pay homage to these first intellectual explorers. Those responsible for embarking on the new DfX believe it will give them some form of competitive advantage, whether they are research or industry based. The first few cases and examples work on a trial and error basis. There is an understanding that change is desired and must occur. As the emerging DfX is a guideline in its infancy, the group undertaking the project has no past experience to work from.

As such several iterations are invariably attempted, with successful iterations promoted to form the basis of the emerging DfX.

Step 3: Developing Heuristics - A Simple Set of Rules

Should the DfX prove fruitful, which in this case implies the DfX results in a product that satisfies the overwhelming need or desire of the time, heuristics for the DfX begin to emerge. Heuristics are rules of thumb that provide a basic framework for solving a problem[8]. A simple oft used heuristic in elementary civil engineering courses the world over is[9]:

"If you are having difficulty solving the problem, draw a free body diagram."

Heuristics encourage other potential practitioners of a DfX to get involved, to add their expertise and experience, and generally to help the field mature.

Step 4: Developing a Process - A Set of Steps for Success

The involvement of more professionals and interested parties eventually helps the field develop a consensus on what constitutes best practice for the given problem. At this point the DfX is near maturation as codified lists of what to do and when to do it appear. Students in schools can learn the basics of the problem and go on to solve their own design challenges armed with the DfX of choice. It is at this stage that the DfX becomes mainstream knowledge and the casual observer may consider the problem posed in the first step fulfilled. This is not, however, the end of the line for the maturation of a DfX.

Step 5: Metrics - A Measure of Success

Occurring almost in parallel with the development of a process is the development of metrics. Metrics are used to validate the results of the process. Typical questions answered by metrics include:

1. Was the process used correctly?
2. Did the process solve the initial problem?
3. How efficient of a solution are the proposed processes?
4. How can the process be improved?

Metrics are typically developed by a group using the DfX. There is no formal oversight of developed metrics outside of the group themselves. It is self-regulated and may change as needed over time.

Although already mentioned, it must be stressed again. Steps 4 and 5 occur virtually simultaneously. Step 5 was listed as the secondary effect of Step 4, as metrics typically quantify the end result of a process. Therefore, they are the natural end point of a process and come after a process in terms of the chronology of events.

Step 0/6: Codes and Standards - A Push or a Pull on the DfX

This last step in the maturation of a DfX is a curious one and difficult to quantify. It can appear as either the first or last step in the process, depending on what DfX you are considering. Details of each case will be provided in the following section. Codes and Standards themselves are a way for the authority in a given geographical area to assert its control over the emerging DfX. Standards and Codes typically quantify the outcome of a given DfX in terms of performance metrics, acceptable levels of by-products during the products lifecycle, etc. In this sense they are analogous to metrics. The difference is these metrics are governed by a professional body with an oversight committee. Any changes to the metrics must be thought through and approved. Any member of the professional body found violating the approved metrics is disciplined or removed from the profession. The two options for the role Standards and Codes play in the maturation of a DfX are detailed below:

1. The initial push maybe initiated by new standards enacted by local governments. An argument could be made that in this case the Standards and Codes put forward by the local authority are merely an extension of the people's will. Therefore the Standards and Codes perfectly embody what Step 1 describes, a driving force that pushes for change in the way engineers develop technology.
2. The Standards and Codes are initiated after the maturation of the DfX according to the steps outlined above. The DfX has been in use for some time, but errors have occurred. To protect the general public's interest, the local authority steps in and develops an expert panel that will regulate metrics pertaining to the DfX in question. Those wishing to undertake engineering design according to the prescribed metrics must be qualified professionals that belong to the oversight committee's organization. If members are found to have ignored the prescribed DfX, consequences will result. This case is identified as the pull on the DfX, as the local authority pulls the DfX under regulatory oversight.

5 Historical Precedent - The Case of DfE

This section does not pretend to provide a comprehensive view of the history of DfE. Rather, a summary of representative works and their effect on the field has been carried out and presented. This section is organized according to the DfX development steps described in Section 3.

Step 1: Catalyst for Change - A Push

In the case of DfE the push has been well documented. It consisted of a groundswell of pressure from the average consumer that led to the adaptation of environmental principles in business activities[10][11][12]. Fiskel asserts this change in attitude began in 1962 with the publication of Carson's seminal work on the topic, *A Silent Spring*[4]. Lagging behind public sentiment but arriving before substantial change had been achieved, government regulations also helped create a push for change[4].

Step 2: Isolated Cases and Examples - A Brave Step Forward

The first cases of successful DfE implementation were published in late 1992[1]. These initiatives were not new - as is seen in Section 5 one early initiative appeared in 1975. These cases helped spur other practitioners to join the field[1].

Step 3: Developing Heuristics - A Simple Set of Rules

The earliest DfE heuristics appear in 1992[1][12][13]. All these heuristics form a base for future practitioners - simple lists of what to do and what not to do. As is expected, heuristics appear after the first few cases and examples become public. The original authors of the concept examine their work in hindsight and provide rudimentary rules by which another practitioner could mimic their success. In the case of DfE, the first heuristics were developed for the American Electronics Association by Brad Allenby based on his work at AT&T. These heuristics were framed for the electronics industry. DfE heuristics continued to grow rapidly over the next few years. Heuristics matured to their final stage around 1996 with the publication of Allenby and Graedel's book on the subject[3].

Step 4: Developing a Process - A Set of Steps for Success

The development of DfE processes began with the development of heuristics for DfE. Processes are - after all - simply more specific heuristics[8]. Processes matured to their final stage only very recently. Fiskel's most recent publication on the subject provides processes for various industries in great detail[4]. This culmination of knowledge allows for any engineer to easily enter the field and begin contributing rapidly. The large time cost associated with developing a DfE has been neatly summarized. Up to this point in DfE history, a huge effort has been put into the development of the DfE idea. This body of work has now been summarized efficiently as processes an engineer may follow. This should impress upon the reader the value of correctly identifying a DfX's evolutionary stage. If a DfX has reached the process level, there is no need for industry or academia to reinvent the wheel.

Step 5: Metrics - A Measure of Success

The development of DfE metrics parallels the development of DfE processes. Metrics for all forms of projects and design appear in Fiskel's latest work on the subject[4].

It should be noted that metrics and processes never truly cease to evolve. As more professionals enter the field, they tweak each process and metric to better serve the design at hand. The latest developments in DfE simply represent a gold standard - any future processes or metrics for a specific DfE application must be as thorough as the currently available processes and metrics to be considered worthwhile.

Step 0/6: Codes and Standards - A Push or a Pull on the DfX

It should be noted that the discussion of Codes and Standards with respect to DfE apply to European, Canadian, and American governments only.

Codes and Standards play an interesting role in the history of DfE. At the beginning, codes and standards reacted more quickly than corporations to the growing trend towards environmentalism[13]. Original DfE practice was spurred by the results of the 1992 Earth Summit among other things[10]. Codes and Standards have been continually evolving. At present, they have not completely finished evolving. European, Canadian, and American governments continue to implement new regulations that further spur the DfE field to design ever more eco-friendly products[4].

For an example of Codes and Standards that lagged far behind the evolving DfX, one must look no further than steel building design codes. Building Design Codes are the ultimate form of Standard or Code. They enforce a certain DfX form, and punish those that vary from the accepted processes and metrics. Steel design was not always governed by Design Codes. In fact, the first steel building code published in Canada appears in 1967[14]. This is five years after the completion of one of Montreal's many steel skyscrapers, The Place Ville-Marie[15]. In this case, Codes and Standard lagged behind the emerging design practice. The Codes and Standards that developed did not seek to *change* behaviour, as they did in the DfE case. In the steel design case, the Codes and Standards were designed to *regulate* the current state of practice. In the latter case, Codes and Standards can be considered the final evolutionary form of a DfX. This is because the Codes and Standards assess the vast body of DfX knowledge, distil the valuable and important parts, and make it illegal to practice the DfX in what is deemed an unsafe manner.

6 Timeline of DfE Developments

This section provides an overview of selected important milestones in the development of DfE. This list is by no means exhaustive.

1975: 3M instituted their 3P program (Pollution Prevention Pays.) This early example of DfE is used in literature as a successful case[4].

1986: Dow Chemical introduces their WRAP (Waste Reduction Always Pays) initiative in their US operations. This initiative would form the basis for one of the earliest cases of successful DfE. Specifically, Dow is referenced by Schmidheiny and Fiskel in their authoritative works on the subject[4][12].

1992, April: Changing Course by Stephan Schmidheiny was published in the lead up to the Rio de Janeiro Earth Summit. This book is one of the seminal works on DfE, although it addresses the issue from a business perspective rather than an engineering one. The book provides a variety of case studies from which DfE practitioners can learn. Again, the majority of the case studies consider the problem from a management or business viewpoint[12].

1992, June: The Rio de Janeiro Earth Summit solidifies the importance of environmental issues in the minds of the general public. Environmentalists are no longer disregarded as a fringe group of fanatics[13].

1992, November: Brad Allenby et al. publish their seminal paper on the topic for the American Electronics Association [1]. This document serves as a true first foray into DfE from an engineering perspective. While mentioning previous projects at various institutions no firm examples are given. Instead, Allenby et al. provide multiple heuristics on the subject such as:

"Senior management leadership and support is critical[1]."

"The firm should develop recognition and reward systems for high quality DfE implementation[1]."

"Material specifications and usage should be consistent with national and international consensus standards[1]."

1996, May: Allenby and Graedel publish Design for Environment. This book displays the evolution of the DfE concept. The book includes nascent forms of a process for introducing DfE to a corporation in the final chapter[3]. Additionally, primitive DfE metrics appear in the appendices of the book[3].

1996: Fiskel publishes his first edition of Design for Environment. While the title is identical to Allenby and Graedel's work, the content signifies the maturation of the DfE concept into the process and metrics stage. Fiskel devotes an entire chapter to process in the workplace[10]. An example of the types of process steps proscribed is as follows[10]:

"Organizational norms must be established that encourage superior environmental performance. This requires evolving from a broad corporate "mission statement" to setting achievable environmental improvement goals and to making employees accountable for meeting or exceeding these goals."

This type of process is an evolution on the concept of a heuristic. The advice proscribed is specific and targets a certain segment of the reader's business operations. At the same time, the advice does not appear in a simple list that can be followed - a recipe for conducting DfE - which is what defines a true process. Fiskel provides elementary rubrics to support the processes described - indeed, he devotes an entire chapter to metrics and their use[10]. The chapter itself provides little in the way of true metrics, simply descriptions of what a metric might look like.

1997: Life Cycle Analysis (LCA) methodology is developed into ISO 14040. LCA is one of many metrics used to determine the environmental performance of a product[16]. As previously stated metrics and processes develop in tandem. LCA was developed over a period of approximately seven years, a time frame that corresponds to the development of DfE processes[16].

2009, June: Fiskel revisits the topic of DfE in the second edition of his book on the topic. This edition signifies the maturation of Steps 4 through 5. Fiskel devotes an entire section of the book to developing processes and metrics appropriate to DfE[4]. He then provides specific examples of a process in action for different engineering fields[4].

1994 - Present: North American and European governments have been implementing regulations that enforce certain DfE principles. The earliest Standard of note was the 1994 Packaging and

Packaging Waste Directive in the EU, which required manufacturers to recover and dispose or recycle packaging associated with their products[4]. This trend continues till today with recent US government forays into environmental regulations for off-shore oil rigs as a result of the oil spill that occurred during the summer of 2010 in Gulf of Mexico[17].

7 Looking Forward

This paper has traced the development of DfE. The trends that have emerged during the development of DfE have been examined. A six step process has been generalized from this examination, consisting of:

1. *Step 1: Catalyst for Change - A Push*
2. *Step 2: Isolated Cases and Examples - A Brave Step Forward*
3. *Step 3: Developing Heuristics - A Simple Set of Rules*
4. *Step 4: Developing a Process - A Set of Steps for Success*
5. *Step 5: Metrics - A Measure of Success*
6. *Step 0/6: Codes and Standards - A Push or a Pull on the DfX*

This paper would be augmented by comparing the development of DfE to other mentioned DfXs, like DfM or DfA. A similar historical analysis would serve to reinforce the conclusions drawn by this paper. Furthermore, a proposed lecture that introduces the concept of DfX development in-line with a discussion concerning the importance of problem definition has been developed. This lecture could be used to validate the proposition that an understanding of problem definition would be bolstered by introducing students to the concept of DfX developments. We intend on measuring the DfX lecture affect by presenting the lecture to students prior to a problem definition assignment presented to first year engineering design students at the University of Toronto. The effectiveness of the lecture would then be measured by comparing assignment outputs in the two previous academic years to the current academic years.

Bibliography

[1] B. Allendy, “The Hows and Why of Design for the Environment,” in *A Primer for the Members of the American Electronics Association*, American Electronics Association, November 1992.
[2] G. Eyring, “Green Products by Design: Choices for a Cleaner Environment,” 1992. Office of Technology Assestment.
[3] B. A. T.E. Graedel, *Design for Environment*. Prentice Hall, 1996.
[4] J. Fiskel, *Design for Environment, A Guide to Sustainable Product Development*. McGraw Hill, second ed., 2009.
[5] R. Holt and C. Barnes, “Towards an integrated approach to design for x: an agenda for decision-based DfX research,” *Research in Engineering Design*, vol. 21, no. 2, pp. 123–136, 2010.
[6] W. McDougall, “The Scramble for Space,” *The Wilson Quarterly*, 1980.
[7] K. MacQuarrie, *The Last Days of the Incas*. Simon and Schuster, 2007.
[8] J. Foster, “ESC101 Lecture Notes,” 2005. University of Toronto.
[9] M.P. Collins, “CIV102 Lecture Notes,” 2005. University of Toronto.
[10] J. Fiskel, *Design for Environment, Creating Eco-Efficient Products and Processes*. McGraw Hill, first ed., 1996.
[11] A. M. Curtis Moore, *Green Gold, Japan, Germany, the United States, and the Race for Environmental Technology*. Beacon Press, 1994.
[12] S. Schmidheiny, *Changing Course, A Global Business Perspective on Development and the Environment*. MIT Press, April 1992.
[13] “UN Conference on Environment and Development.” Online, June 1992. United Nations.
[14] *Handbook of Steel Construction*. Emerson Group, third ed., June 2007.
[15] “Place Ville-Marie.” Online, 2010. SkyscraperPage.com.
[16] A. R. Fabio Giudice, Guido LaRosa, *Product Design for the Environment, A Life Cycle Approach*. Taylor and Francis, 2006.
[17] S. Cox, “BP suffers Washington blame game after oil spill.” Online, May 2010.