INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
8 & 9 SEPTEMBER 2011, CITY UNIVERSITY, LONDON, UK

A CONSTRAINT–BASED MODEL OF THE DESIGN PROCESS

Paul SCUDIERI and Blaine LILLY
The Ohio State University

ABSTRACT
This paper proposes a model of the design process that is based upon the constraints that are present in the design process, the artifact itself, and the artifact's real-world context. Categories of constraints are developed in order better understand the differences and similarities between engineering and industrial design methodologies, processes, education and outcomes. Additionally, the connection between constraints and the long-run evolution of designs is tentatively explored.

Keywords: Design constraints, design evolution, design education, constraint models

1 INTRODUCTION: THE CONSTRAINT CONTEXT

The fundamental goal of the engineering and industrial design disciplines is to conceive and implement the design, fabrication, and operation of artifacts to meet perceived real-world needs. In almost every case, design outcomes are embodied in something tangible—a product, system, or process—that attempts to resolve a given problem in a non–trivial way. “Non–trivial” because these designed artifacts do not exist in isolation: in order for a design to be successful it must adeptly balance the many contextual factors—from performance requirements and market trends to the activity and environment of use—that define a unique design problem.

Our goal here is to look closely at these factors in light of their impact on the design process and on design education. Our hope is that by doing so, insights will emerge that will lead to a better understanding of the design process, design education, and the evolution of designed artifacts. We view the constraint set as the determining element of the design process which defines how design is done, how it is taught, and how it evolves. The constraint landscape is an inherent part of the complex systems within which all designs are created and used. Factors such as consumer preferences, manufacturing processes, material properties, technology, and design decisions themselves all produce constraints that affect the design process and direct the evolution of a design over many generations.

Constraints also exert a profound influence on the processes and methods used to generate relevant design knowledge. Everything from broad and well-established design standards to problem specific design research is in some way constrained by factors related to the context of creation and adoption. In this way, constraints shape the artifact itself as well as the knowledge and skill that conditions the artifact's creation. Because understanding and managing specific constraints very often calls for particular knowledge or skills, constraints also affect the structure of the design team. While a design team cannot hope to predict every constraint that they will encounter, the constraints that are known at the outset will necessitate the inclusion of certain types of expertise and thus, team members. The reverse is equally true: the composition of the design team can and will affect the constraints that are recognized and addressed throughout the design process.

A useful way of thinking about constraints is to build a framework of categories of constraints that can organize and enable thinking about the concepts. The framework we present here is the product of a great deal of thought, and has been subjected to application in a number of different test cases [1]. Because theorizing about the design process can easily wander off into useless abstraction, we will ground our discussion with a single product example that runs throughout the paper. That product is a hobbyist–level digital single–lens–reflex (SLR) camera. We chose this product as an example because, first, SLR digital cameras are a product category that possesses a sufficient, but manageable, level of complexity and secondly, because hobbyist photography is a market segment that has seen tremendous upheaval in the past two decades, as digital technology first disrupted and ultimately destroyed a very lucrative, well–established market in film photography.

2 A FRAMEWORK FOR VIEWING CONSTRAINTS

Our claim is that all product constraints can be viewed as combinations of five fundamental constraint categories. These fundamental categories are: physical, technological, market, social–cultural, and usage. It is important to note that we are taking an expansive view in how we define the term "constraints". Our definition includes hard constraints such as material properties and laws of nature, but also constraints that are imposed by organizations and designers and are often analogous to goals and requirements. Here we briefly define each of the fundamental categories and show how they would apply to the case of the digital SLR camera.

Physical constraints are factors such as weight, volume, density, strength, rigidity, conductivity, etc. These constraints define in some way the physical limits on the artifact. Physical constraints typically do not appear in detail in the early stages of a new design, but emerge gradually as the design progresses. Physical constraints are the dominant factor in determining the range of materials appropriate for a design. While this constraint class is legitimately the domain of all design disciplines, beyond material selection and considerations of size and shape it tends to be the exclusive province of engineers, who devote a considerable part of their formal education to learning how to analyze and manipulate physical constraints. In the context of the digital SLR, the required strength, rigidity, and opacity of the camera body determine the set of feasible materials. The strength and rigidity of the camera body is of course also determined by its structure, but the overall size and weight are constrained on the high end by what a photographer is able to reasonably carry, and on the low end by the need to house all of the necessary internal components. Additionally, the detailed design of the camera body is constrained by the fact that it must be compatible with the system of lenses produced by that particular manufacturer. Each of these lenses is itself subject to the physics of light and optics, as well as the material properties of glass, polymer, aluminum, and stainless steel.

Technological constraints are imposed by the state of technology at the time the design is completed. Technological constraints apply not only to the artifact itself, but also to the other systems of which the artifact itself is a component part: crucially manufacturing technology, but also to distribution, service, and recycling. These constraints are, in general, closely coupled with market constraints. Similarly to market constraints, and in contrast to physical constraints, technological constraints change constantly and rapidly. Some example technological constraints on a digital SLR affect the image capture process with digital media. When digital cameras first appeared on the market, the technological constraint that was most obviously being challenged by manufacturers was the number of effective pixels that the camera used to capture an image. The number of effective pixels is affected by constraints on sensor size, sensor technology, and pixel density to name just three. This focus on effective pixels was evident to consumers as a camera's megapixel rating was for many years the primary specification used by manufacturers to market digital cameras. However, megapixels alone do not determine the quality of the image; other technological constraints such as digital artifact reduction, high iso-sensitivity, and aliasing also play important roles. Other technical constraints related to the manufacturing of the sensor, the camera lenses, and body also impact the camera's design.

Market constraints in design almost always begin with cost and time to market, but in general this constraint category is large and complex. Factors ranging from competing designs and patents to project budget, manufacturing plant size, and expertise of the firm and its competitors all fall into this category. For established designs, or those that are a component of a larger designed system, market constraints can be one of the most influential and deterministic classes of constraints. The most obvious market constraints on the design of a new SLR revolve around how the camera fits into the firm's extant product portfolio. The price point is constrained by the camera's target market as well as its likely and intended competition. This price point then directly constrains many other design decisions, from sensor technology to material choices to the feasible level of technological sophistication included in the camera.

Socio-cultural constraints—probably the most difficult to identify, socio-cultural constraints include factors ranging from how a subset of users understands and approaches a design to the biases, preferences, and learned behaviors that result from experience, education, or organizational affiliations. This is an area where anthropology, psychology, and sociology play a crucial role in product design. For the design of a digital SLR, it is tempting to think of cultural constraints as those design features imposed by the consumer cultures of the United States, the European Union, and Japan, but it is at least equally likely that the cultural constraints having the largest impact on the design emerge from the trans–national culture that has grown up around photographic technology over the past century. Over many years, both professional and novice photographers have developed their own 'language' and developed understandings, methods, and approaches for interacting with cameras and other related artifacts. As technological constraints were finally pushed to the point where digital image quality approached that of film, the digital SLR camera was positioned to represent, for many photographers, their first foray into the new digital medium. Accordingly, these cameras would have to operate with respect to cultural constraints that had been developed over years of shooting film: snapping a picture, changing lenses, and adjusting exposure settings all needed to fit within the film shooter's mental models and understanding of how to operate a camera. These constraints are seen most clearly when one realizes that digital SLR cameras look and feel quite similar to film–based SLRs — even though there is no film inside.

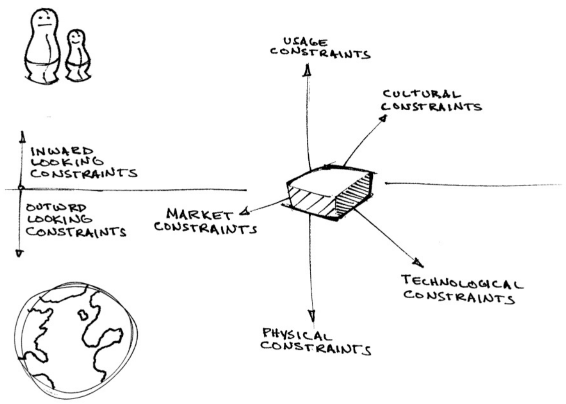

Figure 1. Comparing 'inward looking' with 'outward looking' constraints

Usage constraints include both physical and cognitive ergonomic factors, and can be explored and used in order to evaluate existing designs or to generate totally new designs and directions. New usage constraints, or constraints that remain unaddressed by designers, are also regularly addressed and designed for by small segments of the user population after the artifacts release [2]. These usage constraints are often quite closely coupled with socio-cultural constraint factors, as we have noted above. There are many instances in which the design of the digital SLR was influenced by usage constraints — the following examples are representative but far from being the only instances. Decisions regarding which camera controls needed to be adjustable on the body of the camera and which could be accessed through a digital menu, as well as which settings would be controllable while looking through the lens—most notably aperture, focus, and shutter speed—were all constrained by design decisions regarding use. Physical ergonomic constraints like weight, size, and feel, as well as cognitive ergonomic constraints such as how to design the digital menus for ease of understanding and use also played a large role in determining the final design of the first digital SLR cameras.

The five categories of constraints outlined here tend to fall into two large classes: those that apply to the artifact itself regardless of who uses it, and those that exist between the artifact and a specific user. Physical, technical, and, to a lesser degree, market constraints are factors that apply to the thing itself, without any consideration given to any particular user or stakeholder. In effect, these *outward looking constraints* are global constraints that apply broadly to all users. In contrast, the *inward looking constraints* comprised of usage and socio-cultural constraints (and some market constraints) exist between a product and a user. They only manifest themselves when the artifact is used by a specific person in a specific, real-world context—hence the need for design teams to develop personas and scenarios to uncover these types of constraints when creating new products.

There are obviously other types of constraints that exert an influence on product design or artifact evolution, but we claim that these other constraints can be constructed and explained as combinations or derivatives of the five general categories highlighted above. For example, *aesthetic* constraints are typically driven by market, socio-cultural, and (to some extent) physical factors, while *performance* constraints are typically defined by some combination of physical, technological, use, and market constraints. Thus, while the constraint categories listed above are far from being a complete list of every constraint that influences artifact design and evolution, we assert that they are the most *basic* set of constraints that can be defined, combined, and used as building blocks to construct and explain the design constraints that all engineers and industrial designers routinely encounter.

3 THE CONSEQUENCES OF CONSTRAINT SELECTION

From the examples above it should be clear that the lines dividing the classes of constraints can become quite blurred; design problems rarely fit neatly into any single class. Additionally, there is a great deal of interaction among the categories as constraints in one class typically interact with other constraints within that class as well as constraints in other classes. This can be illustrated by looking at the problem of material selection for the body of a digital camera. The material choice itself (say, a high–end engineering thermoplastic versus aluminum or magnesium) is directly affected by physical constraints such as the weight of the camera and its rigidity, as well as the ability of the body to keep the camera's sensor shielded from all light. But the design decision about what material to use for the camera body also interacts with market constraints: the cost of the material itself, the state of the firm’s current manufacturing processes (can they be adapted to produce the body from a new material?), as well as questions regarding how this material might compare to direct competition from other producers (can a thermoplastic body compete against higher quality metal bodies in the hobbyist market?) must all be resolved. At the same time the physical constraints established by this design decision affect future usage constraints such as the weight and feel of the camera—hobbyist photographers tend to want a substantial camera that has enough weight to steady a shot, but not so heavy that it becomes a burden to carry. Technological constraints are also effected, particularly with respect to the fabrication of the body.

Through this example, one can see how every design decision helps to further define the artifact itself and establishes constraints that interact across the constraint classes. *Every design decision creates a more highly constrained environment in which all future design decisions are made*. While it is possible to operate relatively free from constraints early in the design process, constraints become numerous and more difficult to navigate very quickly as the effects of even small design decisions begin to pile up. As those design decisions and their created constraints begin to interact with one another across all five of the constraint classes, the act of balancing these constraints becomes even more difficult. One could even say that any singular design decision is an attempt to manage the existing constraints, but at the same time that decision imposes new constraints whose consequences designers are forced to consider and balance throughout the remainder of the design process.

While we propose that every design decision creates new constraints, the constraints that are created can, and do, vary based upon the particular decision that is made. The result is that not only does the cumulative “weight of constraints” increase throughout the design process, but the different design decisions greatly affect the set of constraints that comprise this “weight”. Accordingly, the set of constraints that designers must address and balance is not one that is ‘set in stone’ at the outset of the process: each successive design decision has the potential to vary the constraint set and thus affect possible future design directions.

In the case of the digital SLR, for example, the choice of material for the camera body was initially constrained by price, feasibility of manufacture, and material properties, but that still left the designers with many possible choices. The potential to choose steel, thermoplastic, magnesium, aluminum, a carbon composite, or a number of other materials existed at the project's outset. However, once a given material was selected, a number of new constraints arose with which designers had to contend throughout the remainder of the design process. Many of the constraints that were created depended directly upon that material choice; the designer's potential choices about manufacturing methods, camera architecture, fit, finish and tolerances, as well as the weight and feel of the camera were all constrained differently depending on the designers’ initial choice of material.

4 IMPLICATIONS FOR DESIGN EVOLUTION

While we have written about these constraints as relatively static entities, they are in fact constantly evolving; as the world changes and evolves, so do the associated constraints. As constraints change over time, so too does the design process and its outcomes—most often a direct result of the evolving constraints. Products themselves also have the ability to alter the set of constraints; when a product is released, it has the power to greatly expand user capabilities, break through technological constraints, and escape existing archetypes in ways that will forever transform user expectation. Not only for itself, but for all products to be subsequently released. *In this way, designs are constantly changing their* *context in a manner which effectively evolves the constraints upon which future designs are founded.* This mutually influential relationship between artifacts and constraints leads to designed systems that behave in ways which are strongly reminiscent of biological evolution [3],[4]. This has far reaching implications as designs themselves often create new constraints in the context of an "evolving" dominant design, thereby defining new standards and norms that future product design activity, and future products, must conform to.

As constraints and products interact and evolve alongside the surrounding real-world context, one of two outcomes will likely occur: the design will eventually fail or be unable to perform an intended function, as the result of evolving constraints; or, in the face of evolving constraints, assumptions will indicate that under some future conditions the design, as it currently exists, will fail or a different design will do a better job at meeting the current constraints [5].

Because constraints evolve as the result of new designs and a rapidly changing real-world contexts, these two outcomes will *eventually* force a re-design or the creation of an entirely new design. This helps to explain why so few designs persist unaltered, even for relatively short periods of time. Even great designs eventually succumb to evolving constraints. For example, the design of something as simple and seemingly static as the push-pin (invented in 1903) [6] has evolved as the result of evolving constraints—evolving manufacturing technology and ever more demanding business goals have given rise to a push pin that, while looking completely familiar, is designed and manufactured in an entirely new way. *Given a long enough period of time, every design will evolve as a result of new and shifting constraints.* A point of clarification is that we are not claiming that every physical artifact evolves—in fact, artifacts themselves most often remain static—but rather that the underlying design evolves over the course of successive product generations as a result of the surrounding constraints.

5 CONCLUSION: IMPLICATIONS FOR DESIGN EDUCATION

By describing designs as a solution to a problem posed by a set of constraints we are in no way trying to write creativity or skill out of the design equation. Simply focusing on constraints in a specific way is not, in and of itself, a formula for successful design. Rather, engineers and industrial designers rely on skill and creativity *within the boundaries* of their constraints. Even armed with a better understanding of the contexts that constrain their designs, no small measure of personal skill and creativity is required in order to develop innovative and successful design solutions—whether that be consumer products or highly technical engineering solutions. In fact, design history is filled with examples of new or challenging constraints that, when placed in the hands of talented designers, quite often resulted in brilliant designs.

Despite the similar goals of engineering and industrial design, there are often great differences in terms of the two disciplines' knowledge, processes, methodologies, and outcomes. These differences are often the result of the constraints that each discipline chooses to focus on and optimize their process around. This focus shows up most clearly in the design of curricula which design and engineering students must master in order to become practitioners. While most design disciplines do provide at least some measure of consideration to all of the major categories of constraints, every designer is inherently resource limited [7] and therefore must make choices about where time, money, creativity, etc. are best spent. As it stands, the current ways by which designers and engineers prioritize and address constraints are inherent in the education and practice of the two disciplines.

In general, it appears that classically trained engineers will direct their attention to the physical and technological constraints, while industrial designers tend to focus on the cultural and usage constraints, with market constraints a secondary focus for both groups. Our contention is that if we as educators modify our curricula so that all of our students have at least some understanding of the constraints that are typically 'outside the fence', then our students are likely to leave the university much better prepared to confront real design challenges from their first day on the job.

At Ohio State University, we have created a four–year framework that is currently being put into place to guide the design education of our mechanical engineering students. This framework assumes that the entire design process must be followed at every stage of the students' education, from the first year to the last. What changes from year to year is the set of constraints that we apply to the problems students are assigned. First–year students are led through a very structured process, and typically solve very well–defined problems in a highly constrained design space. Second–year students are given more advanced skills, such as CAD and machine shop training, in the context of a well–defined design problem, but are then required to design and fabricate a solution to a much more open–ended, ill–

defined problem. By their final year, students will be able to start with a vague need, do necessary research, frame the design problem themselves, and then fabricate a functional prototype. Throughout the process, the focus will be on creating functional descriptions of the problems, and understanding how the constraints evolve as the design evolves.

By viewing the design process and design outcomes in light of the constraint framework set out here, we believe that every practitioner engaged in design will better understand not only their "own" constraints, but also those constraints that are primarily the domain of other disciplines. Doing so will allow them to conceive and implement artifacts that are more thoroughly considered with respect to *all* of the constraints present in the design's real-world context.

REFERENCES

[1] Gill, C.L. and Lilly, B.W. The Challenge of Sustainability: Designing for Resilience. In *Engineering and Product Design Education Conference*, Salzburg, Austria, August, 2006.

[2] von Hippel, E. *Democratizing Innovation*, 2005 (MIT Press, Cambridge).

[3] Fleck, J. Artifact↔activity: the coevolution of artefacts, knowledge and organization in technological innovation. In J. Ziman (Ed.), *Technological Innovation as an Evolutionary Process*, 2000, pp.248-266 (Cambridge U.P., Cambridge).

[4] Mokyr, J. Evolutionary phenomena in technological change. In J. Ziman (Ed.), *Technological Innovation as an Evolutionary Process*, 2000, pp.52-65 (Cambridge U.P., Cambridge).

[5] Vincenti, W.G. *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History*, 1990 (Johns Hopkins U.P., Baltimore).

[6] Antonelli, Paola. *Humble Masterpieces: Everyday Marvels of Design*, 2005 (Regan Books, New York).

[7] Simon, H.A. *The Sciences of the Artificial*, 1996 (MIT Press, Cambridge).