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INTEGRATING ENGINEERING AND PRODUCT DESIGN FOR SUSTAINABILITY'S SAKE

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ABSTRACT:

Although 'sustainable design' has become widely accepted as a necessary component of the educational preparation of designers, architects, and engineers around the globe, it seems that 'sustainability' is a concept lacking a precise definition. Here we propose that sustainability is not an attribute of products themselves, but is a necessary characteristic of the production and distribution system of which they are a part. Further, we assert that sustainable systems must exhibit some degree of resilience, which is defined as the capacity to support adaptive capability. Here we explore some ways in which product design practitioners and educators might look to ecology as a source of inspiration for thinking about the challenges of creating a sustainable system of products in a global economy. Because these concepts by their nature encourage thinking across disciplinary boundaries, we also explore ways in which product designers and engineers can work together to put these concepts into practice.

1. INTRODUCTION: RE–THINKING SUSTAINABILITY

As designers and design educators, we bear some level of responsibility for the flood of products produced by the global economy every year. A visible consequence of that responsibility is the strong and growing emphasis on 'sustainability' whenever we meet as a community to discuss the future of design as a discipline.

One rather curious aspect of the conversation about 'sustainability' and 'sustainable design' is the lack of precision surrounding the words themselves. A certain level of ambiguity is to be expected, given the wide range of disciplines involved in the product design process, and the relatively recent growth of interest in these concepts. However, we believe the need for more effective action, in the face of globalization pressures, requires that we begin to think more precisely about what 'sustainability' actually means, in terms of the products we produce, and the practitioners we educate.

We begin by confronting the often unstated assumption that it is possible to create 'sustainable products'. In fact, as ecologists have long noted, sustainability is not *"… an end state that we can reach; rather, it is a characteristic of a dynamic, evolving system."* (Fiksel, 2003). In fact, products can promote and encourage environmental responsibility by their users, but strictly speaking they cannot be 'sustainable' in and of themselves. A consumer product can be designed to use environmentally sensitive materials, to consume minimal energy, and to allow for easy disassembly and re–use, but there is no guarantee that such a product will somehow find its way back to the manufacturer for re–use and/or remanufacturing, unless the *system* in which it 'lives' is designed to capture it, remove it from the waste stream, and treat it in a way that promotes sustainability of the system. On the other hand, a production and distribution system that is based on the idea of long–term sustainability would also be capable of capturing and re–using products that might not have been designed specifically with an eye to environmental stewardship. In that case, the product's design might impede recovery and re–use of materials, and might require high levels of energy and resources in its manufacture. Nevertheless, it would still be recoverable, and in that sense would be less damaging than if it were embedded in a non–sustaining system.

Every product, no matter how large or how small, is embedded in a hierarchy of ever–larger systems that culminates in the global economy. We assert that the focus of the design discipline should be on creating *sustainable product systems*, not sustainable products. When seeking insights into the nature of sustainable systems, one is confronted with the somewhat overwhelming task of finding relevant ideas within the large and growing field of systems theory. Our own search for a relevant conceptual framework has led us to the discipline of theoretical ecology. Over the past several decades, one of the most prolific and important thinkers in this area is the Canadian ecologist C.S. Holling, who originated the concept of system resilience over thirty years ago (Holling, 1973). His succinct definition of a sustainable system, on which we base this paper, is *"…the capacity to create, test, and maintain adaptive capability"* in the face of changing inputs (Holling, 2001). In this paper we look briefly at the concept of resilience, both in the context of living ecological systems, and as applied to product families in a market environment. Because the ideas we propose require the cooperation of practitioners from many disciplines, in the concluding sections we offer some ideas as to how the various fields related to design, in particular product design and product engineering, can come together to create resilient product families that will support truly sustainable systems of production, distribution, and use.

2. RESILIENCE IN BIOLOGICAL SYSTEMS

When looking for inspiration in the field of theoretical ecology it is necessary to begin by acknowledging the great differences that exist between biological organisms living in complex, highly adaptive ecological systems, and human–designed products competing for market share in the global marketplace. On a fundamental level, one must take note of the fact that organisms have an inherent 'drive to survive' that products do not possess: products of course are completely passive, and their survival is totally dependent on how well they are designed, and the connections this design engenders with the user of the product.

In addition, all organisms, down to the level of single cell animals, are able to respond to their environment and react to it: they belong to the category of complex adaptive systems. In attempting to apply insights from biological systems to designed products, we begin by admitting that at present, no products that we are aware of possess an inherent ability to adapt to changing environments, although it is worth noting that software applications do exist, e.g., computer worms and viruses, that appear to be approaching this capability. Nevertheless, when we think of complex adaptive systems in terms of products, we are referring specifically to systems composed of a family of products *and the design team that is responsible for creating them*. In other words, the intelligence needed to adapt and survive is provided by the design team.

Returning to Holling's definition, the concept of *adaptive capability* is clearly at the heart of his conception of sustainability. This implies that systems that are sustainable over the long term cannot be static: they must possess the ability to change within a changing environment. As a measure of the system's ability to adapt to change, Holling in 1973 introduced the idea of *ecological resilience*, which he defined as a measure of the system's vulnerability to unexpected or unpredictable shocks (Holling, 1973). In contrast to *engineering resilience*, or robustness, which is typically taken to be a measure of the speed at which a system returns to equilibrium after being perturbed, ecological resilience *"…emphasizes conditions far from any stable steady state, where instabilities can shift or flip a system into another regime of behavior – in other words, to another stability domain. In this case, resilience is measured by the magnitude of disturbance that can be absorbed before the system is restructured with different controlling variables and processes."* (Gunderson and Pritchard, 2002). A graphical representation of the concept is shown below (Fig.1). The ball represents the current state of the system in question. The ball at rest at the bottom of the curve represents the system in a possible equilibrium state; resilience is the amount of disruption the system can accommodate, i.e., the distance the ball can move laterally, before the ball comes to rest in another stable orientation. It is important to note here that because the shape of the curve represents a living system, it will itself change over time; in other words, the ball might not necessarily move, the curve might 'move under it'.

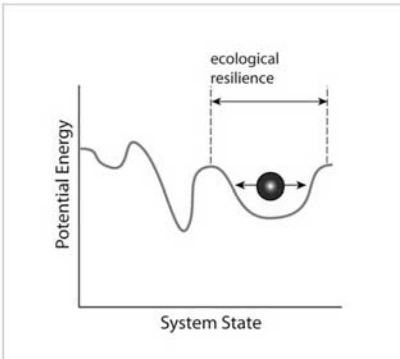

Figure 1. Graphical portrayal of ecological resilience, after (Gunderson, 2002)

Because it is a measure of persistence under changing conditions, ecological resilience is a defining characteristic of systems that are sustainable over the long term. Our claim is that this definition of resilience can be a useful metric for assessing the degree to which product systems exhibit long–term sustainability. Resilient systems can be evaluated in terms of four key characteristics: *diversity*, the existence of multiple forms and behaviors; *adaptability*, or the flexibility to change in response to stresses; *efficiency*, or minimal resource consumption; and *cohesion*, the existence of unifying forces or linkages (Fiksel, 2003).

3. RESILIENCE OF PRODUCT FAMILIES

In applying the concept of ecological resilience as a measure of product viability, the four sub–headings listed above – *diversity, adaptability, efficiency*, and *cohesion* – can be quite useful in guiding our thinking. In terms of product attributes, *diversity* can be seen as the number of contemporaneous products within a product family; *adaptability* is a measure of how quickly product generations appear in response to changing market or cultural trends; *efficiency* naturally encompasses energy and resource use, both in fabrication ('embedded energy') and in product use; and *cohesion* can be seen as a measure of how easily a product can be identified as a member of a larger product family. These concepts are useful when assessing products and product families that are currently on the market, and when thinking about how best to develop a family of new products.

In order to assess the usefulness of this framework, we have begun to look at products that have shown market longevity. Even though these products are often not environmentally sensitive, they have shown the essential quality of persistence over time, and we look to them for clues in achieving long product life. We believe it is important not to lose sight of the fact that if we truly want environmentally responsible products to have an impact in the market, they must be desirable to consumers. Our experience as a society, especially in the United States over the past thirty years, has shown that appeals to the conscience of the consumer will only go so far: we cannot expect customers to pay more for socially responsible products, or to settle for less in the way of usability. It is up to designers to create irresistible products that are also environmentally sensitive. For this reason, we look to long–lived products for instruction and inspiration.

Examples would include very simple devices such as paper clips and lead pencils, but also products that survive by virtue of an emotional connection with a group of users, e.g., Harley–Davidson motorcycles. In addition, we have explored product families that have evolved over time, such as the Kodak family of one–time–use cameras (OTUC) shown below (fig. 2).

Figure 2. A small subset of the Kodak OTUC family – the evolution of the waterproof version

Since their introduction in 1987, these cameras have gone through numerous changes while dominating their market segment for two decades. With reference to the four characteristics of resilient systems – *diversity*, *efficiency*, *cohesion*, and *adaptability* – this product line exhibits all of them. The product family is quite diverse, with new variations appearing on the market on a more or less continuous schedule; they are highly efficient in terms of energy and material use, with approximately 90% of the components in each camera either re–used or recycled; they cohere as a product family with a brand identity that is extremely strong; and finally they are quite adaptable, as shown by their ability to survive even as the remainder of the market for film cameras has evaporated (Lilly and Gill, 2006).

The capacity of these products for adapting provides a particularly interesting insight into how a product family can survive a major change in its market environment. As digital technology has revolutionized the market for image capture and storage, companies that thrived in the era of film–based photography have been under tremendous pressure to either adapt to rapidly changing technology, or perish. At Eastman Kodak, one response was to abandon the mid–range film camera market while moving selected components of these cameras down–market. A specific example of this strategy is the two–element *Ektanar*© lens, which was previously available only on Kodak's more expensive cameras. This high–quality lens was successfully introduced into the OTUC family in 2001. Because the modular system architecture of the cameras was able to easily adapt to a change in the lens configuration, Kodak could continue to exploit this successful technology, even as the market for mid–range film–based cameras disappeared. By doing so, they made a significant improvement to their down–market product, bolstering its market position, and thereby enabling it to survive in an age dominated by digital technology.

It is important here to reiterate what we are *not* saying. We are explicitly not claiming that the Kodak OTUC family is 'sustainable'. One can reasonably argue whether or not creating a product line that consists of components that are extensively recycled and re–used, which is the case with the cameras, is environmentally more sound than selling a standard camera that requires that only film be changed. That is not our point: we believe the OTUC family clearly shows aspects of resilience that can be adapted by design teams to many other product lines. In fact, there are two distinct ways in which users bond with products, which we call 'low road' and 'high road', following Stewart Brand in his classic book on the uses and re–uses of architecture, *How Buildings Learn* (Brand, 1996). The camera family is a good example of a 'low road' approach to product resilience: the user does not experience any significant emotional attachment to the product itself, but is drawn to the idea of having a camera that is extremely *efficient*, in the sense that one chooses it for situations where one does not mind losing or damaging it, while still getting very good photographs. By way of contrast, the Harley–Davidson motorcycle is an example of a 'high road' approach to resilience: the *cohesive* factor, i.e., the brand, is so strong that not only are the motorcycles themselves the subject of an emotional connection by the user, so is the experience of riding the motorcycle with others, along with the regalia, etc. We have more to say about the role of the user experience in creating resilient product families in the next section.

4. THE IMPACT OF USER EXPERIENCE ON RESILIENCE

When products do not respond to the changing needs of users or changing market conditions they become undesirable and hence, unused. By the same token, products often outlive any conceivable useful lifetime simply because they are designed to do so: the materials used, and the combination of materials with processing methods that make disassembly and separation impossible negatively impact the appropriate life of the product. Simply put, creating products that last much longer than their useful lifetime is not conducive to the overall sustainability of the larger system. In other words, designing for long product life does not in and of itself support sustainability – sometimes the optimal product life is a short one, assuming that the materials can be easily captured and re–used.

4. 1. PRODUCT LIFE, USEFUL LIFE AND OBSOLESCENCE

The toy industry in particular is replete with products that are not well designed in terms of useful life. Products are designed primarily to appeal to a parent's perceived notion of need, rather than meeting the changing needs of the growing child. Toys are a classic example of a market in which the consumer and the user are not the same person, leading to dissonance between what the purchaser expects and what the product delivers to the user. Many toys do not reflect essential characteristics of resilience such as adaptability, efficiency, or cohesion, nor do they respond to the user's changing needs. They are not embedded in a system that can evolve and support new 'stability domains' such as new games, new functions, or new environments, in order to extend the useful life of the product as the child matures.

Figure 3. Three different toys that display different levels of adaptability

These products quickly become obsolete or unused, but the materials used in their construction can last for decades in landfills. Obsolescence in this context can be the result of the child not liking the toy from the first moment, the child growing bored with the product quickly because it does not allow enough variation to stir the child's imagination, or simply because the child very quickly outgrows the toy. The US market is inundated with products such as the Star Kitchen© by Chicco shown on the left in Figure 3. This toy doesn't afford any alternatives for a child's imagination, and it does not adapt to any other kind of activity – in effect, it is an island in a child's playroom. Adults make the purchase with the assumption that the child will actually enjoy it for some time, or at least long enough to justify the 60USD spent. Once the purchase is made, however, the parent has no options: if the child does not like the toy, the energy, materials, money, and effort consumed in its fabrication, transportation, and distribution are in effect wasted. The toy itself might find its way to an attic or in the best case, to a garage sale; otherwise, it's on its way to the landfill, where it will remain intact, and buried, for decades.

The second toy shown in Figure 3 is the LeapFrog Interactive Learn & Groove Musical Table©. It has two configurations that allow for adaptation, based on the child's growth. As an infant, the child can use the table top without the legs, with the parents' assistance. As the child becomes able to stand independently, the legs can be added to create a full table. While this product clearly affords more adaptability than the Star Kitchen, it is also more dependent on the child liking the activity itself: once again the parent has few options if the child loses interest. On the other hand, the table has a range of activities built in: an interactive, bilingual activity table, which entertains the child with songs, twinkling lights, instrument sounds, and lots of things to spin, roll, slide, open and close. At least in this case, the toy appeals to a wider range of the child's senses, and provides greater opportunities for play.

The third example shown is the very well–known and much–loved modular building system from LEGO. This is a very long lasting product system that does in fact possess all four resilience characteristics:

- *Adaptability:* the products are designed specifically to grow in difficulty as the child moves through different maturity levels, by affording different levels of complexity in games and structures to build. The toys adapt well to single and multiple player activities, and most importantly, they allow for 'open ended' play (unlike the toy kitchen) in which the child's imagination is the only limit to how they are used.

- *Diversity:* after many years of producing simple construction kits of various sizes, over the past two decades LEGO has diversified the product line to include many different types of kits, including the highly technical LEGO Mindstorms kits for teenagers. While the kits can be seen as a move away from the 'open–endedness' mentioned above, they are still compatible with the larger product family.

- *Efficiency:* LEGO products all work together, so a user never has to worry about potential compatibility issues among products; in addition, the individual components themselves are produced to very high tolerances and material standards. The basic building blocks can be produced cheaply and efficiently, in various colors, can perform many tasks, and are designed to maintain their high quality for generations of children (Muren, 2006).

- *Cohesion:* LEGO has created a very strong brand identity over the life of the product line, and legendary customer loyalty; products are instantly recognizable, from the Duplo sets for toddlers to the Mindstorms kits for teenagers and adults. Designing parts that are interchangeable across the entire product line is perhaps the strongest example of product family cohesion that we know of. In fact, an entire user community, complete with websites, has built up around this product line.

4. 2. ADDING VALUE AND LONGEVITY

With children's products, product longevity is especially dependent on how strong an emotional connection exists between the product and the child or the parent. Parents tend to keep toys that are associated with a specific event in the child's life, with their own childhood, or with the parenting experience. Many companies now recognize the need to stage 'experiences' in order to add value to the product; in the toy industry we can find examples of several strategies. The focus of these strategies is on designing experiences in order to engender greater customer loyalty and increase the perception of value (Pine and Gilmore, 1999).

An outstanding example of these strategies is the 'adoption' concept created around Cabbage Patch Kids©. When a child acquires a doll, the doll is not 'purchased': rather, the child 'adopts' the doll, which comes with its own name, birth certificate and adoption papers. Parents can take their children to the 'hospital', where the birth and adoption process is staged to create an emotional attachment between the child and the doll. Another method that Mattel has implemented with this line of products is to develop an emotional attachment through a process that Pine and Gilmore call 'collaborative customization'. The parent can order a doll with specific physical characteristics so that the doll resembles the child it is intended for. It is less likely that a parent will ever discard a toy, especially a doll, that was fabricated exclusively for their child.

Kodak has also implemented "experiential" components with many of their products. They have created an entire family of products under the "Easy Share" tag promising the consumer a meaningful experience in capturing and sharing memories. With the OTUC family of products, Kodak utilizes a strategy that Pine and Gilmore call 'cosmetic customization', as shown in Fig. 4, in which four OTUC cameras are sold in a bundle, with packaging and labeling appropriate for weddings. The idea is that the cameras are distributed to the guests at the wedding reception, where they are encouraged to take candid photos of each other, and leave the cameras behind, for the hosts to develop. These cameras have become a ubiquitous feature at weddings in the United States over the past decade, and once again show how Kodak is able to extend the longevity of a product that 'should be obsolete' well into the age of digital photography. By focusing on those situations in which an expensive camera will be a hindrance, and by creating some sort of bond between the user and the product, they are able to keep the camera alive in the marketplace.

Our intent in offering these examples is not to encourage designers to extend the life of products that are essentially useless but to advocate for an appropriate length of life. A challenge to designers and engineers is how to embed characteristics of resilience in the product system, and in addition, provide users with an emotional experience that brings value to the product. This is one of the strongest lessons to be learned from reading Brand's *How Buildings Learn*: when humans perceive value in a product, they will act to maintain it. Buildings traditionally are so expensive that they are routinely maintained and re–built without much thought. One task of design is to provide a sense of value in products so that users will want to maintain them, rather than discard them, when the product cannot easily be returned to the producer.

Figure 4. Kodak Max Wedding Edition

An interesting alternative to providing value to the user is to provide value to the manufacturer and remove the burden from the user. The Kodak's OTUC cameras deliver a service and an experience to the user, but the company maintains control of the product itself. In effect, when a customer purchases one of Kodak's OTUC cameras, they are actually purchasing the film and leasing the camera. The fact that Kodak will capture and re–use and recycle the camera itself is not known to the customer, and in fact, is not important: the customer cares only that he or she receives good value for the money, in the form of high quality photographs from a camera costing less than 10 USD. We suggest that this model could be applied to many other products: the product creates a valuable experience for the user, but the firm maintains control over it.

Perhaps the single most daunting aspect of using recycled products and materials is capturing and sorting them, once they enter the post–consumer waste stream. This Kodak OTUC strategy in effect keeps the product from ever entering the waste stream. However, this is not a new strategy: Xerox, for example, followed a similar approach in leasing their copying machines for similar reasons. We believe that it is one way to build more resilience into a product system. After all, it is the product that poses the problem with recycling and re–use: if we can provide the experience without losing control of the product, many of these issues will disappear.

In effect, what we are proposing is two distinct ways to look at products. In the first, the user becomes the owner of the product, and the strategy should be to design the perception of value into the product, so that the user will see the product as worthy of being kept, maintained, and even rebuilt, in the same way that 'high road' buildings are preserved. The second product category includes those 'low road' products that are unlikely to have 'value' in the consumers' eyes; in this case, the strategy should be to design systems that capture the products for re–use, recycling, or reclaiming.

All of the ideas we have proposed here clearly depend on the design team having a very wide range of expertise and a diverse set of disciplinary backgrounds. The challenge for us as educators has been to build structures that will allow students to come together across the barriers imposed by a very 'silo–based' organization, the American university. In the next section, we present some ideas we have experimented with over the past three years of collaborating, in the hope that they might spur further discussion.

5. CROSS–DISCIPLINARY METHODS FOR DESIGN

In this paper we have presented several ideas that we believe are essential to doing product design with the goal of promoting a more sustainable global economy. We believe that the demands of creating resilient product families requires a 'total systems perspective': the entire context of the design, including the total user experience, as well as cultural, economic, and psychological constraints, must be taken into account from the very earliest stages. This can only be achieved by design teams that draw on expertise from a much wider range of disciplines than has been the case in the past.

As educators in industrial design and engineering, we are acutely aware of the difficulty of explaining each other's contributions to colleagues in our own disciplines. Engineers persist in conflating design with 'style', and quite often think that industrial design is merely about 'making the box look pretty'. Engineers are trained to think quantitatively, and often tend to be wary of information that does not come with numbers attached. Designers, while they may tend to be more open to the contributions of engineers, often seem to believe that engineers 'just don't get it' when it comes to design. We often hear variations of the theme that emphasizing design functionality at the expense of aesthetics results in designs that are 'over engineered'.

We believe that effective design requires a strong emphasis on the functionality of the product, but as we have attempted to show in the previous section, it is crucial to focus on the 'soft side' of design as well in order to create products that will generate value in the minds of their users. We strongly believe that the most successful products, such as Apple's iPod, are those that marry extremely well–thought–out functionality with elegant aesthetics. However, elegance and functionality are by themselves not sufficient to create resilient product families. These products will require design teams that include not only product design and engineering, but also the perspectives and insights of allied fields such as cognitive psychology, field anthropology, and ecological systems theory, among others.

We have noted elsewhere the important role that product architecture can play in enabling resilience (Lilly and Gill, 2006), (Gill, Lilly, and Chan, 2006). Here we would like to emphasize a few of the tools that we have begun to develop and use with our team of graduate students from product design and engineering. The intent of these tools is twofold: to provide a common visual language that the students can use to communicate across disciplinary boundaries, and to create tools that force students to confront important questions as they proceed through the design process. Our efforts to date have focused primarily on building visualization tools that are based on systems engineering methods, expanding the scope to focus on use, process and the environment in which the system resides.

One of the most useful analysis tools in systems engineering is the functional decomposition chart (FDC), which is an essential tool for systematically dissecting complex systems (Ulrich and Eppinger, 2003). Starting at the top with a simple 'black box' model, this method iteratively decomposes the system into smaller and smaller functional elements, until the user is satisfied that the most basic functional level is reached. By examining functions and constraint sets at different levels in a system's hierarchy, the design team can expand the possibilities for innovation. (Figure 5) While this method is most often used to define the architecture of the product, we believe that there is an opportunity to expand the system boundary from the product itself to the product and the user in the corresponding 'environment'. By including the user, the environment and the interactions among them, more questions regarding the product system at different levels arise earlier in the design process.

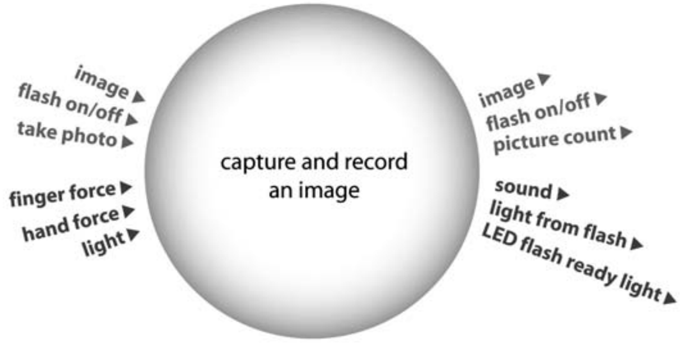

Figure 5. Top-level functional description of the OTUC

We believe that by embedding the function decomposition diagram in a contextual representation (Fig. 6), it ceases to be merely a tool for engineers, and becomes a tool for product designers as well. All the complexity that was 'in the box' before is still there, but now additional demands are placed on it as well. This technique can reveal desired and undesired interactions between components, functions, related products and user needs. Equally importantly, the design team can use the diagram to acquire possible insights for designing products as part of larger systems.

The representation shown in Figure 6 is intended as a snapshot of a visualization tool, currently under development by our research team, that eventually will be used for system and product design as well as analysis. The system will provide design teams with a much more complete picture of the product system in action, at several discrete levels of detail. At each level, the functional composition of the system, along with all relevant constraints, is easily shown. Flows of information, mass, and energy, both intended and incidental, are mapped in a way that clearly shows which flows are internal to the system, and which are external. With such a system it will be possible to zoom in to the individual component level in a specific design, or to zoom out to the highest level of the product family in the context of larger economic and ecological systems.

6. CONCLUSIONS

In this paper we have presented several of our ideas regarding sustainability and resilience, grounded in ecological systems theory, and applied them in the context of the design of consumer products. We have shown several examples of products that point to possible directions for a future in which products and families of products are parts of a truly sustainable economic system. We believe that while it is certainly not possible to model products in markets as biological organisms in ecosystems, these ideas can be very useful as analogies when looking at the behavior of product systems.

We have also tried to strengthen the case for multidisciplinary collaboration in the larger field of product creation and fabrication, and have used our somewhat limited case of interdisciplinary work to show how tools can be developed that will encourage this type of system thinking across the disciplines. There is a clear need for continued work, especially at the undergraduate level, to encourage our students to think and read outside the confines of their own discipline, to gain a better understanding of what the other fields engaged in design can bring to the effort. There remains much work to be done in this area, and we look forward to participating in further developments.

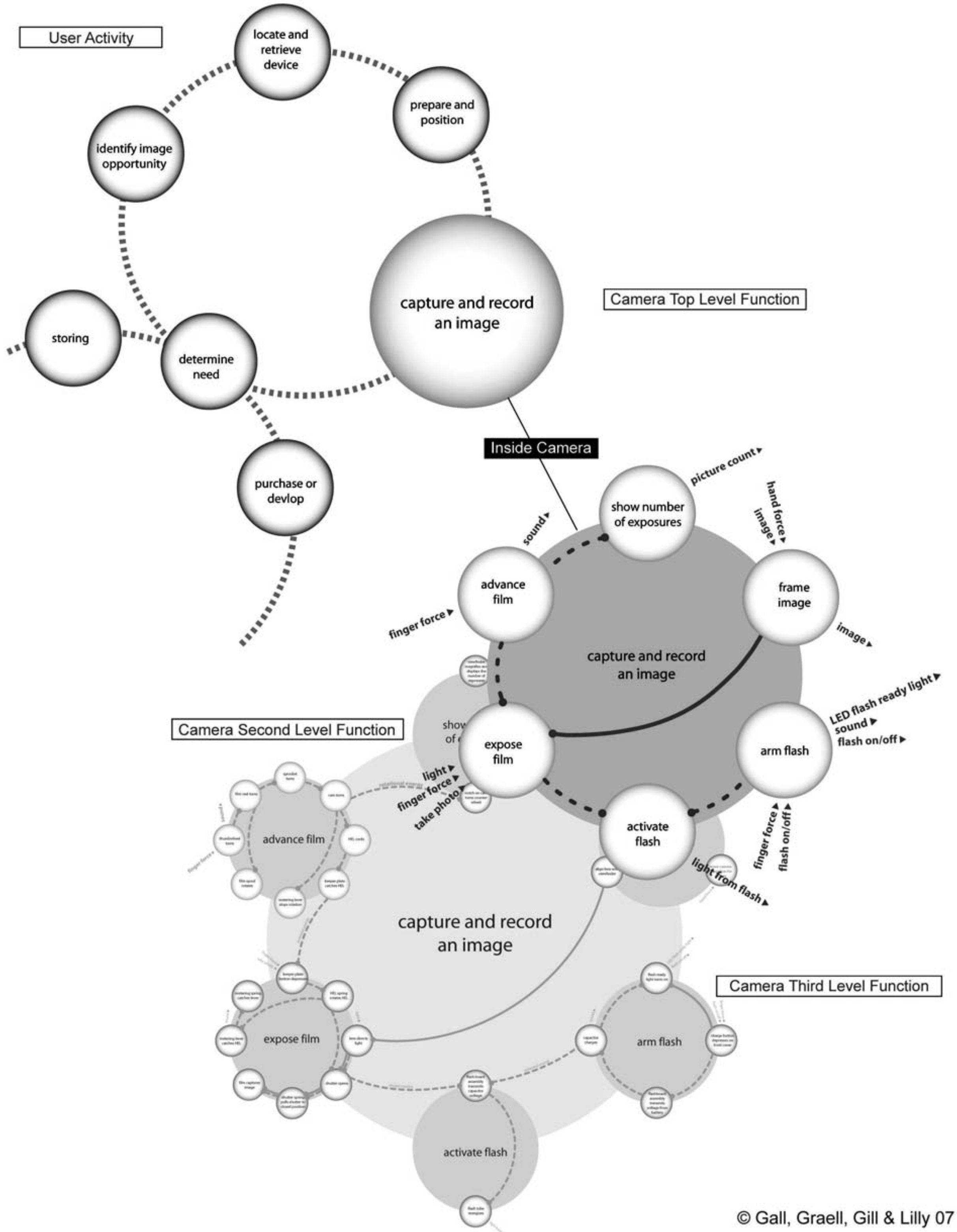

Figure 6. Graphic tool for capturing system functions (Gill and Lilly, 2007)

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