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Bridging the Gap between Eco-Design and the Human Thinking System

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Abstract: Technological progress has enabled widespread adoption and use of consumer electronics, changing how global society lives and works. This progress has come with immense environmental cost, including extraction of scarce materials, consumption of fossil fuels, and growing e-waste challenges. Eco-design has emerged as a promising approach to reduce the environmental footprint of electronics by integrating sustainability-oriented decisions early in the product realization process. However, most approaches focus on the product itself, not on the consumer who ultimately decides how to purchase, use, maintain, and dispose of the device. This article presents a new framework to guide designers in developing products with features that encourage consumers to use them in an environmentally sustainable manner. The Sustainable Behavior Design (SBD) framework links common design concepts (ergonomic, emotional, preventative, and interaction design) with core aspects of the human thinking system to create features to make users aware of their behavior and decisions (reflective thinking) or result in sustainable behaviors even when users are unaware (automatic thinking). The SBD framework is demonstrated using a case study on a smartphone, a high demand product. The reimagined smartphone design integrates solutions addressing both automatic and reflective thinking systems, potentially reducing life cycle impacts by almost 30%.

Keywords: electronic products; energy; sustainable design; human thinking system; consumer behavior

1. Introduction

The role of the designer is shifting from functional (making products fun and intuitive) to one that is instrumental in reducing a product's environmental impacts, such as energy or material consumption. It is generally assumed that well-designed objects integrate the human mind through consideration of user needs, and therefore the product should be easy to understand and operate [1]. Accounting for how people think is essential when designing "environmentally-friendly" products, but also challenging, as environmental impacts are fundamentally linked to the processes in which the product is manufactured, used, and disposed, on which the user may have limited influence.

For products such as consumer electronics, significant sustainability challenges span their life cycle, encompassing environmental impacts, social equity concerns, and economic tradeoffs (as described in numerous references, e.g., [2–9]). The environmental relevance of consumer electronics continues to grow, as most interactions in a household involve an energy-consuming device [10] and the number of electronic devices owned in an average household has been steadily increasing over time [11]. At the same time, many household consumers are generally not aware of, not in control of, or choose to ignore the environmental impacts associated with their use of electronic devices.

For example, users may not know how much electricity is consumed when a device is in use or charging or have the ability to specify the fuel mix used to create this electricity [12]. While significant progress has been made to reduce the environmental impact of individual devices (e.g., reducing standby power mode via the Energy Star program) [13], factors such as shifting ownership patterns, shortened innovation cycles, changes in consumer preference, and increased consumption of existing products have so far negated product-level efficiency improvements [14].

Further, many of the relevant environmental impacts of consumer electronics occur farther upstream or downstream of the consumer. Many mobile products, like smartphones, have significant upstream environmental impacts associated with raw material extraction and manufacturing [15,16] or downstream impacts such as potential release of toxic substances (lead, mercury, and arsenic, among others) in uncontrolled environments at end of life [8]. While not a direct consequence of consumer behavior, these impacts are magnified by unsustainable behaviors or decisions the user does influence [14], such as frequently replacing still working devices, which requires new products to be manufactured and additional waste to be managed.

Sustainability of consumer electronics can be strongly influenced by designers [17,18] who have early involvement in the product realization process and the ability to determine the pattern of behaviors and interactions between the product and user through specification of features, form, finish, ergonomics, and durability, among other factors [19–21]. To create a well-designed, desirable object that also has reduced environmental impacts, designers generally employ two types of approaches: (1) production or supply-side strategies [12,17] and (2) human or user-centered or demand-side strategies [17,22].

1.1. Supply-Side Strategies

Production or supply-side strategies focus on improving the environmental impacts associated with a product's upstream manufacturing and production processes [17,23]. Common production or supply-side eco-design strategies include, but are not limited to dematerialization, minimizing the use of toxic materials, incorporating recycled materials, reducing packaging, and applying energy-efficient manufacturing methods [12,24,25]. Supply-side strategies are particularly important for consumer electronics, since the majority of these devices' life cycle impact occurs during manufacturing stages, and significant environmental gain can be realized by extending product lifespan and deferring manufacturing of a new product [5–7]. Application of supply-side strategies to consumer electronics has created innovations such as the *iameco* personal computer, which features hardwood casing and durable, easy to maintain components that extend product lifespan and avoid manufacturing of a new device [26]. Another recent innovation is the *Fairphone 2*, which is designed to enable the user to replace worn or broken parts and extend the product's service life to as long as five years [27].

However, a major limitation to existing supply-side strategies is that consumers often do not have direct control over the design and manufacturing of the products they purchase, or may not have the knowledge or desire to make decisions that enable the full realization of eco-design benefits. For example, to encourage more efficient recovery of high value computer components, a design that is completely modular could reduce labor and operating costs at a recycling facility [28]. However, this benefit entirely depends on the consumer deciding to bring the device to a recycler, rather than leave it in the basement or dispose of it in a landfill. These challenges underscore the need for additional policy and services to support and enable the full benefit of supply-side strategies, such as user-friendly electronic waste collection systems, markets for product resale, and parts and support for upgrading devices [9,26,29]. Thus, green production practices do not necessarily translate to sustainable purchasing and usage behaviors [17,23] since net benefits can be reduced by adverse consumer behavior and choices [8].

1.2. Human- or User-Centered Strategies

To complement sustainable supply-side strategies, human- or user-centered design (also referred to as demand-side) strategies are also employed [17,30]. Demand-side strategies, unlike production ones, focus on how consumers use or interact with a product and how consumer behavior can be influenced to create sustainable outcomes [17,22,31]. These design strategies begin with understanding the consumer, and then base changes on meeting consumer needs, goals, traits, and values, ultimately seeking to improve the interaction of the product and user [17,32].

A range of human-centered strategies has been leveraged, which generally fall under two categories: (1) changing consumer behavior by the design of the product; or (2) designing products and functions to align with or mirror the way people actually use products [17]. An example of the first strategy applied to consumer electronics is designing a computer display to prompt a user to put it into sleep mode, as a way of providing information or feedback to the user to prevent unsustainable behaviors [22,33]. An example of the latter strategy is the "blind" mode proposed by Rodriguez and Boks [12] whereby televisions or computers may automatically operate with screens dimmed when users are not actively watching programs, but instead may want to listen or have television programming, music, podcasts, or videos on in the background. Designing a product to align with how people actually use it may result in less negative impacts by eliminating redundant or missing functions, but still fulfilling the overall function desired by consumers.

While the human- or user-centered design strategies have been recognized as an important part of changing consumer behavior, additional guidance is needed to create a product that influences consumer behavior [34]. The human-centered design research field generally focuses on developing conceptual frameworks, case studies or research studies. For example, the Wever *et al*. "functional matching typology" tries to integrate multiple strategies to encourage environmentally sustainable behavior [17], with limited application to a case study of a smart meter system and only focused on one concept of eco-feedback. Using data from empirical studies, Lofthouse developed a holistic framework combining guidance, education, and information to ensure eco-design tools align with the culture of industrial designers [35]. Lilley identified a range of passive to aggressive strategies to encourage socially sustainable behaviors for the appropriate use of mobile phones in public [22]. Lilley and Wilson [20] provide a methodology to assess behavior impacts from an ethical perspective, where the relative benefits and limitations of achieving behavioral change without the user's knowledge can be evaluated. Pierce *et al*. identified a list of design actions and strategies based on a field study and survey of how people interact with energy consuming devices and systems in their homes [10]. Selvefors *et al*. [36] integrates user studies on mobile phones in a project with Ikea of Sweden with a six-step design approach to determine suitable strategies to influence users' resource consumption behavior. However, the case study recommendations are discussed in general terms and some are not directly related to the product itself (e.g., using renewable energy sources at home).

While human- or user-centered design strategies have been recognized as an important part of changing consumer behavior, there is concern that limited practical guidance is available to encourage multi-disciplinary design teams to create a product that influences consumer behavior [34]. While the "design for sustainable behavior" field has developed many approaches, the terminology is inconsistent [37] and may not be intuitive for team members without a design background. For example, the "Design with Intent" or "DwI" methodology [34,38], which considers both inspiration (e.g., representing six different perspectives that can influence behaviors) and prescriptive (e.g., formulating the design challenge based on a range of target behaviors) modes, was applied to a case study focusing on how a customer interacts with an automatic teller machine [34]. However, the DwI method is complicated and focuses on how the designer thinks rather than how the user thinks. The application of this framework does not explicitly seek to improve environmental sustainability of the product (e.g., consumers do not have the ability to influence energy consumption), although that may be a potential outcome. More recently, the Behavior Intervention Selection Axis (BISA) [39,40] was created to combine popular sustainable design techniques with digital media to change behavior using data from in-depth qualitative user studies. This approach examines solutions with behaviors over an axis of influence; strategies range from being under the user's control to the product being in control [39,40], but the resulting environmental performance is not validated.

While both supply- and demand-side strategies continue to emerge to address environmental challenges associated with consumer electronics [17,20,22,41,42], the two approaches are rarely integrated [17]. This lack of integration is particularly critical in the case of consumer electronics, since the product environmental footprint is so heavily influenced by processes occurring well upstream or downstream of the consumer, and yet the consumer's unknowing behaviors can easily magnify these impacts. Not surprisingly, the adoption of sustainable behavior has been slow [43,44] and a challenge to maintain [45], particularly since electronic products have become so embedded in our daily routines [10], and as such, are not likely to prompt consumer concern over environmental impact [12]. Moreover, sustainable practices and awareness are often tied to convenience and low effort [46]. As a result, there is no clear agreement on the type or level of intervention strategy that is deemed acceptable and effective [22], as shown by the variety of sustainable design approaches noted in Lilley and Wilson [20].

We propose that effective integration of supply- and demand-side eco-design strategies can be realized by accounting more fully for the human thinking system: understanding how consumers think about the products with which they interact. Thaler and Sunstein's "Nudge Theory" suggests that people think in two different ways, automatic and reflective [47]. The *automatic thinking system* is uncontrolled, effortless, unconscious, fast, and skilled, while the *reflective thinking system* is controlled, effortful, self-aware, slow, and rule following [47]. An example of automatic (or "situational" [40]) thinking (acting unconsciously or without any effort or awareness) is when a driver suddenly brakes after noticing someone running into the street. The driver thinks fast and acts unconsciously in response to the events unfolding in front of them. In the case of reflective thinking, people plan for, are aware of their actions, or react based on previous experiences or events in that moment of time [47]. For example, a driver might brake when he/she sees a police car in the distance or stop to let people cross a street. The driver sees the police car or stop sign, thinks intentionally, and acts slowly. Understanding and designing for both aspects of the human thinking system can help mitigate behaviors that might result in undesirable or negative environmental impacts (e.g., unnecessary energy use or frequent product replacements). The human thinking system is central to the axis of consumer *vs*. product influence in decision making related to behavior changes as noted earlier.

Therefore, the goal of this research is to develop and apply an integrated suite of eco-design strategies that demonstrate how designers can address both aspects of the human thinking system to guide development of environmentally sustainable products. This Sustainable Behavior Design (SBD) framework is based on the way the consumer thinks (automatic and reflective thinking) and then builds in design goals, human-centered design concepts, and specific techniques to address unsustainable behaviors. This framework adapts and builds on existing methodologies and frameworks, such as the BISA model described above [20,22,36,38]. Unlike these approaches, the SBD framework begins with and is centered on both aspects of the human thinking system, thus providing a holistic and more effective way to influence user behavior and choices during the use phase. Ultimately, a designer can use the SBD framework presented here to influence and guide how people use a product, thereby, directly reducing key environmental impacts that are associated with the use phase and indirectly reducing environmental impacts from upstream manufacturing processes and downstream waste management systems.

To demonstrate the utility of the SBD framework, a smartphone is reimagined and presented with a new design. Smartphones are part of a group of devices that are rapidly growing in consumption levels and functionality [11]. As noted previously, managing the environmental impacts of this product system has been further complicated by the rapid changes in consumption, ownership patterns, and technological innovations [11]. Therefore, incremental improvements stemming from supply-side design strategies are not sufficient in light of our increasing purchasing behaviors and rising household energy consumption [14,48]. To move beyond small changes, policy and design strategies need to account for how a device is produced and then used by consumers [14], all while providing the function and style demanded by the consumer [48].

2. Methods and Materials

As SBD framework was created to guide the development of sustainable products. The springboard for the SBD framework was the "human thinking system" [30], or how people think and behave. The framework was also built upon contributions of other approaches related to the axis of influence [40] and human behavior theories such as Nudge Theory [47]. Next, the literature was reviewed to understand and explore how common strategies and techniques related to ergonomic, interaction, emotional, and preventative design (referred to in this paper as "anticipatory design") have been used in other case studies and frameworks. These strategies were then linked to either reflective or automatic thinking systems and applied to address well-known and literature supported sustainability challenges associated with the smartphone, as a representative case of consumer electronic products.

The SBD framework is comprised of four elements: (1) design goals intended to address negative or "unsustainable" behaviors, (2) specification of which aspect of the human thinking system is targeted, (3) existing design concepts that align with the goal and thinking system, and (4) specific examples of design techniques that demonstrate how the eco-design goal can be realized. The utility of the SBD framework was demonstrated with the smartphone case study to illustrate how one could successfully integrate the human thinking system in product design. The case study focused on four different challenge areas or goals. For each goal, design solutions were identified to mitigate or stop unsustainable behaviors that (1) are well known as causes of product environmental impact and (2) would affect both aspects of the human thinking system (reflective and automatic). Some of the solutions were considered primary, *i.e.*, directly influenced by the industrial designer, while others would be thought of as enabling or secondary. Secondary strategies often focus on provision of supporting services (e.g., apps or software), which could improve product sustainability, but would be not directly attributable to the designer's decisions. Finally, the SBD framework was used to reimagine a smartphone.

The environmental performance of the new smartphone design was validated using basic environmental metrics. While many environmental impacts result from production and consumption of consumer electronics, cumulative energy demand (CED), which includes both direct (electricity consumed while using the device) and indirect (*i.e.*, upstream fossil fuel) inputs, is a well-established predictor of environmental impacts including, but not limited to the resource depletion, ecotoxicity, acid rain, and climate change [49,50]. This limited validation is intended to be a simple metric that can inform and provide feedback to the decision-makers early in the design process, an extension that is often omitted when design frameworks are proposed. Although this estimate can be further quantified by life cycle assessment (LCA) when product design is finalized, such an extended analysis is outside the study scope. Specifically, theoretical environmental savings were calculated from a baseline annualized CED that assumed a 2007 smartphone model and an average lifespan of 2.5 years [14]. The annualized result was based on total manufacturing impact normalized by the original (2.5 year) or new (3.5 year) lifespan plus the use-phase energy consumption in that year [14]. Additional energy savings associated with the avoided material and electricity demand were estimated using the hybrid LCA approach described by Ryen et al [14] and supplemented with data from the ecoinvent databases [51].

3. Results and Discussion

3.1. Development of the SBD Framework

The SBD framework incorporates design concepts and techniques that focus on both aspects of the human thinking system, presenting a holistic and unique opportunity to help consumers select the right products and possibly avert potential unsustainable behaviors when the product is being used. As shown in Figure 1, using the SBD framework begins with the designer setting specific goals to prevent or minimize well-known unsustainable behaviors. Solutions to these goals are then proposed using design concepts associated with subconscious behavior (automatic thinking) and those that intentionally guide behaviors and decisions in a certain direction (reflective thinking). Finally, the concepts are translated to specific techniques that can help meet the eco-design goals. For example, allowing a user to personalize a product or allowing the user to set the order and layout of the device based on his/her interests and habits will increase the connection with the device [52], and potentially leading to a longer service lifespan.

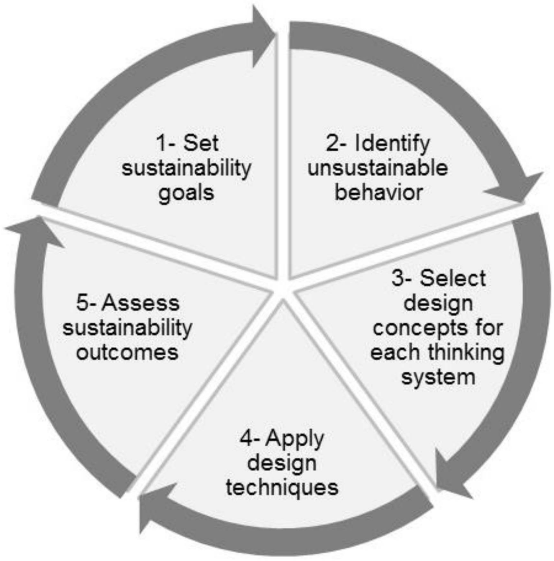

Figure 1. Iterative process of applying the SBD framework.

What makes the SBD framework unique is that the final design solution accounts for both aspects of the consumer's thinking system (Figure 2). For example, to influence a behavior reflectively, we use interaction design concepts to communicate or interface with the user so that they will knowingly shift their behavior based on environmental motivations. Interaction design focuses on the interchange between people, products, services, and our environment [53]. Another way to encourage change based on reflective thinking is to anticipate how a consumer may behave and then leverage design features to prevent that outcome [22]. In this model, we are referring to this concept as "anticipatory design". Both interaction and anticipatory design concepts (and their respective techniques) are under the reflective thinking system because the design makes the user aware of their behavior and then purposefully uses the information to modify his or her actions.

The SBD framework also integrates design concepts associated with automatic thinking, specifically with emotional and ergonomic design. These design concepts encourage a strong attachment and connection between the user and product without the user necessarily recognizing it, but are accomplished in very different ways. For example, emotional design attempts to satisfy the user's needs and convey his or her beliefs, thoughts, history, and feelings [54]. On the other hand, ergonomic design considers physical aspects of the human body and how it interacts with the product, so the product becomes easier, more comfortable, and more desirable to use [55]. The attachment between a user and the product may extend the product lifespan and prevent premature obsolescence [28]. Both emotional and ergonomic design are under the automatic thinking system because the user is not aware that their decisions or actions are connected to environmental outcomes.

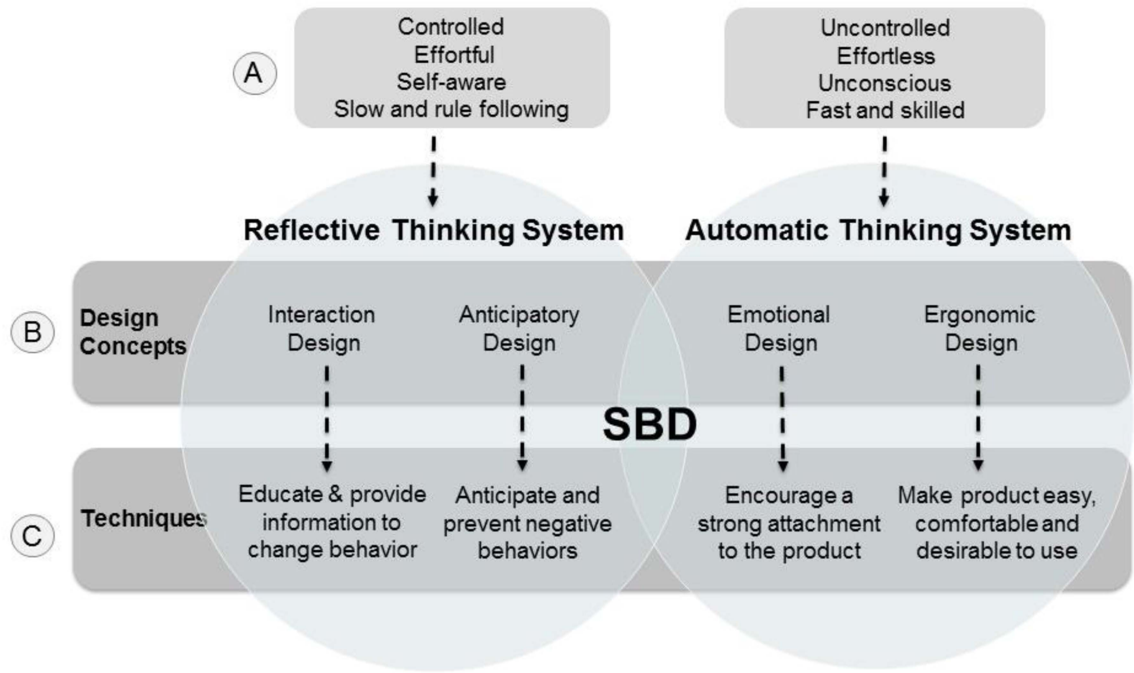

Figure 2. The SBD framework incorporates (**A**) traits associated with how people think (reflective and automatic), (**B**) appropriate design concepts, and (**C**) product-specific design techniques.

3.2. Application of SBD Framework—Smartphone Case Study

The use of the SBD framework is demonstrated with the redesign of a smartphone. In this case study, four goals are identified. These goals are based on the potential for reducing environmental impact (e.g., energy consumption, waste generation, *etc*.) and/or are associated with daily behaviors (e.g., dropping/misplacing the phone) [37]. Each goal relates to both aspects of the human thinking system (automatic and reflective), ultimately influencing the sustainable use of the smartphone. The four goals include reducing the frequency of purchase, reducing energy consumption, minimizing physical damage, and encouraging sustainable end of life (EOL) management, as described below.

The SBD framework provides a non-exhaustive array of potential primary and secondary design pathways to solve the unsustainable behaviors. The primary strategies are accomplished directly by industrial designers during the design phase. Secondary or enabling solutions such as an accessory, app, or software can also be an effective way to change user behavior, but are not directly created by or under the control of the industrial designer. For example, to enable a consumer to update or repair a phone part, service providers such as large and small repair shops or even self-help videos would play a critical and complementary role. The intent is not to constrain design to the strategies suggested here, but rather to demonstrate a thought process and illustrate simple techniques that designers may not have realized can change behavior or lead to environmental savings.

After a design has been developed using our SBD framework, prototypes can and should be evaluated further by life cycle assessment to determine if the design effectively achieves the stated sustainability goals or if the goals need to be altered. As noted in Figure 1, application of the SBD framework is meant to be iterative, like other types of human-centered design (e.g., Design Thinking [30,32]). While not shown in this case study, the addition of a prototyping and testing phase to the SBD framework would improve the overall design of the product by providing needed feedback during the design process to the decision makers [20] and helping them select techniques and features that are acceptable to the users [39]. Below, each goal is defined and described in the context of a range of solutions that impact both aspects of the human thinking.

3.2.1. Goal 1: Reducing Purchase Frequency

Smartphones are characterized by rapid replacement cycles more attributable to "fashion obsolescence" than to true technical obsolescence [56]. Short replacement cycles are linked to negative environmental impacts, since the manufacturing phase of smartphones, and consumer electronics in general, is the greatest contributor to product impact [5,6,56,57], and marginal use phase energy efficiency gains associated with technological progress from one product generation to the next cannot offset this manufacturing impact [58]. The first goal, reducing the frequency of purchase, seeks to diminish the unsustainable behaviors resulting when consumer desire "the next best thing" or purchase a new smartphone instead of repairing an existing one. Wireless providers also indirectly influence this behavior with contract upgrades and service agreements. New service agreements (e.g., AT&T Next^{sm}) allow people to upgrade to a new device at any point [59]. As a result, the lifespan of a smartphone is only about 2.5 years on average, but often as low as 18 months [14]. As shown in Figure 3, a range of potential design concepts and techniques can be applied to achieve this goal by integrating both aspects of the human thinking system. For example, a designer could influence the user's automatic thinking through emotional design, by allowing the user to add his or her memories, symbols, or images to the frame itself. Therefore, the user may be less likely to give up their phone since it is a reminder about something special that happened in his or her life [60].

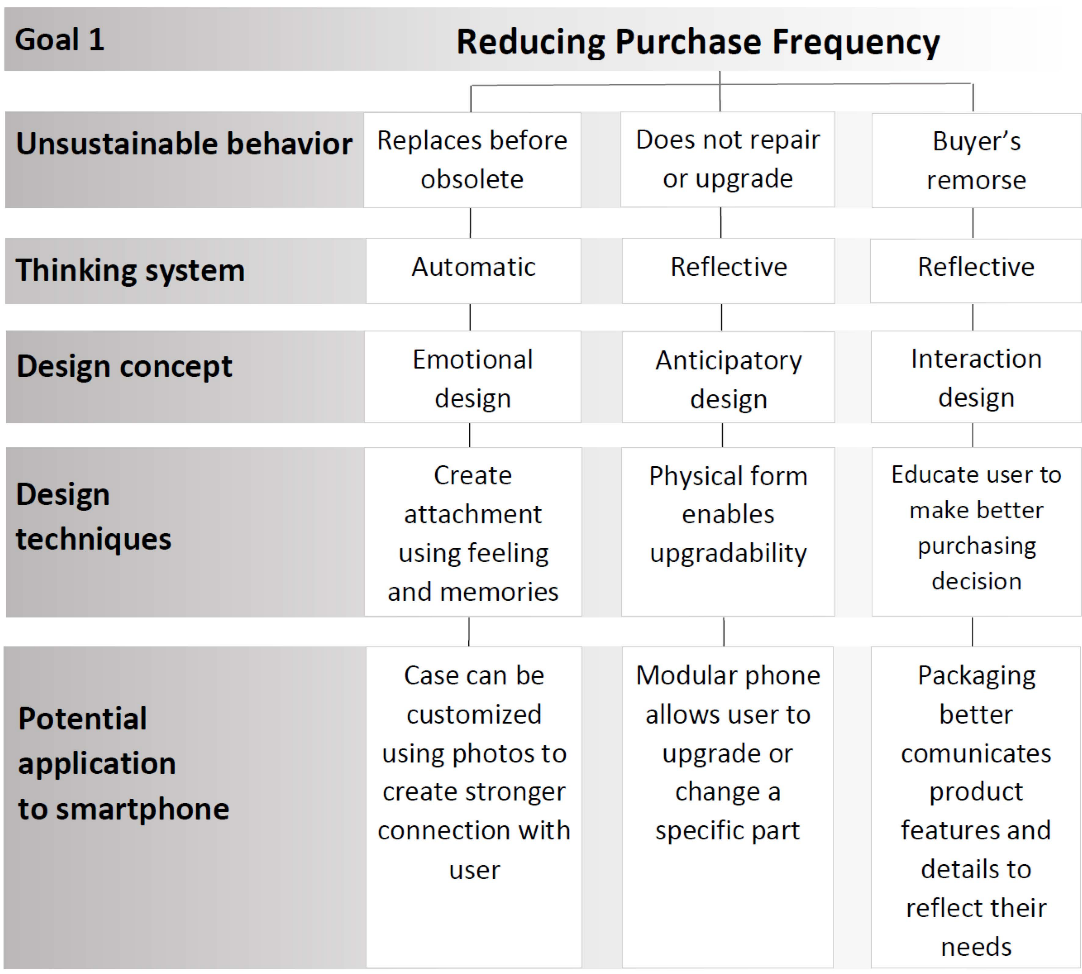

Figure 3. SBD framework applied to meet Goal 1, "Reducing Purchase Frequency": examples of how images, modular design, or packaging extend product lifespan.

3.2.2. Goal 2: Reducing Energy Consumption

As shown in Figure 4, Goal 2 recognizes three types of unsustainable behaviors that center on direct and indirect environmental impacts associated with the smartphone battery. For example, overcharging and undercharging a battery can reduce the life of the battery [61,62] and may result in unnecessary energy consumption. For example, a battery charged only 40%, but running at 104 degrees Fahrenheit will result in a 15 percent decrease in battery life capacity over one year [61]. If left fully charged but plugged in all day, the battery lifespan decreases by 35% over the year [61]. To address this concern, a plug can be designed to be slightly difficult to detach while the phone is charging, but easily removed when the battery is fully charged (Figure 4). Design strategies proposed to address this challenge also suggest providing information to the user that will guide them towards making an environmentally sound charging decision or change the form of the smartphone to inherently lead to greater cooling.

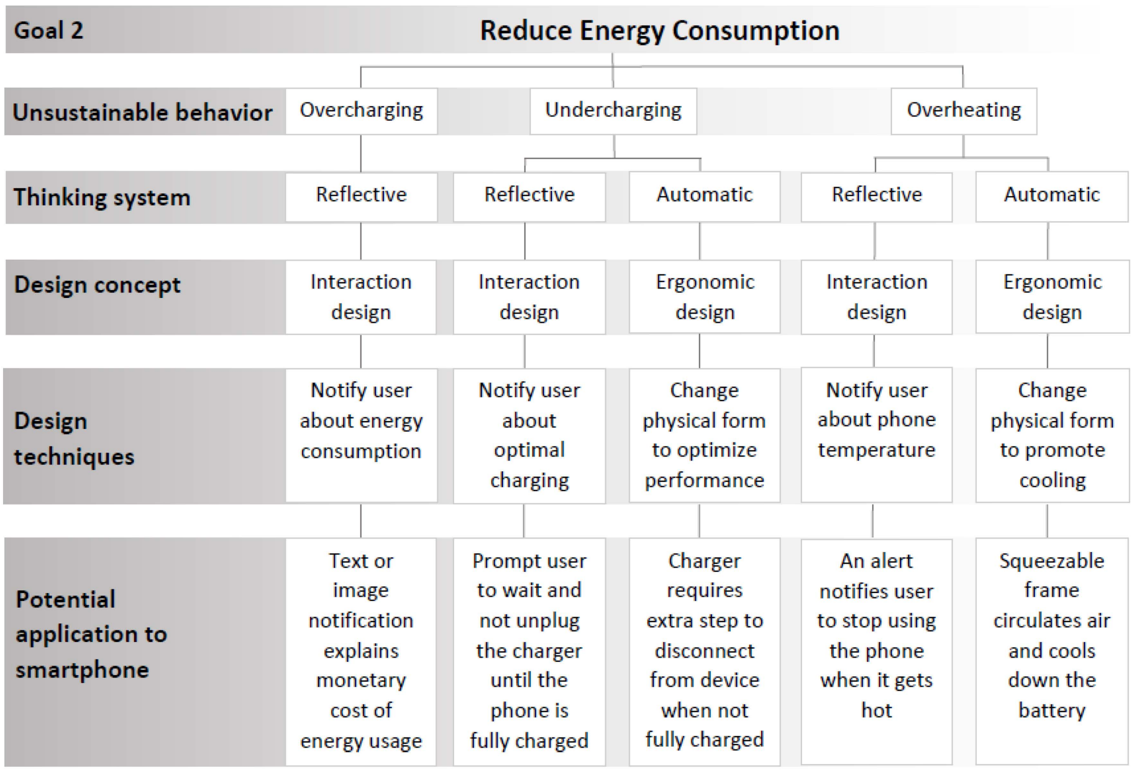

Figure 4. SBD Framework applied to meet Goal 2, "Reducing Energy Consumption": examples of how notifications or changes in the product form can result in lower energy consumption and extended product lifespan.

3.2.3. Goal 3: Minimizing Physical Damage

As shown in Figure 5, Goal 3 seeks to reduce behaviors that result in physically damaging the phone, which is clearly linked to shortened lifespan and more frequent product replacement cycles [63]. One example of this behavior that the framework seeks to address is dropping or losing the device or accidentally exposing it to water or extreme temperatures. As shown in Figure 5, using an easy-to-grip or slip proof material on the smartphone frame will enable the user to hold onto the device and be less likely to drop and cause water or shatter damage. In addition, incorporating durable and shatterproof materials in the frame will prevent damage by protecting the phone even if it is dropped. In both these examples, changing the external form of the product prevents or minimizes damage without the user's awareness or active participation.

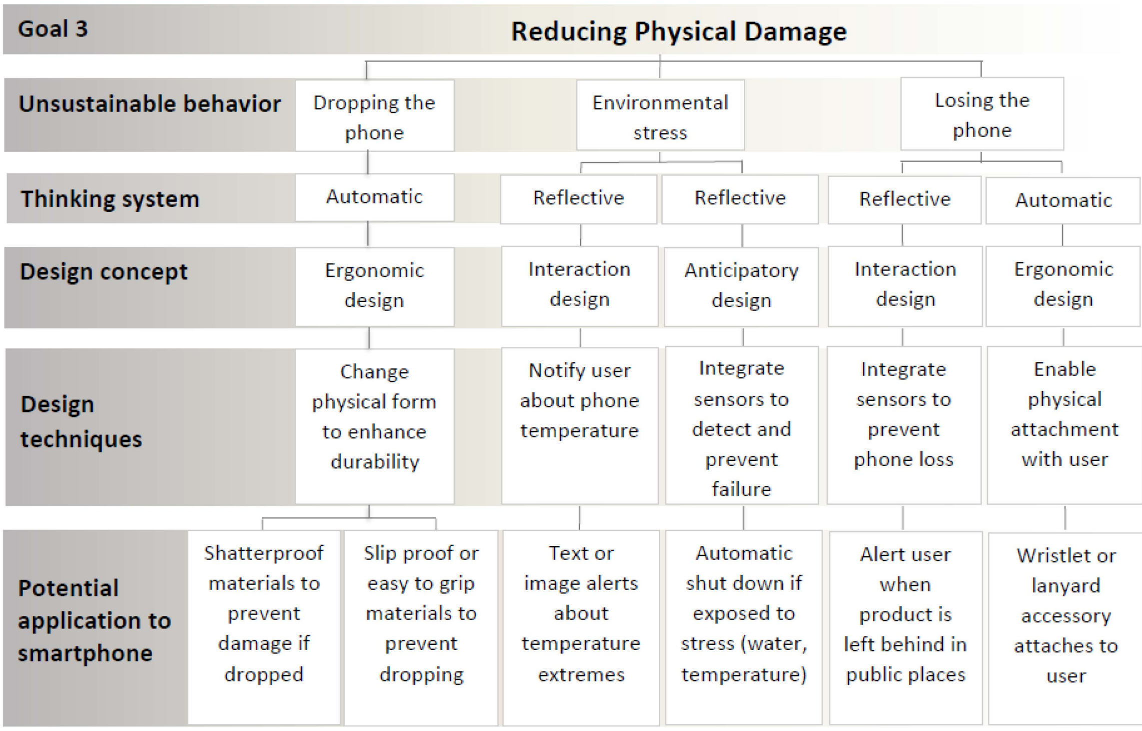

Figure 5. SBD framework applied to meet Goal 3, "Minimizing Physical Damage": examples of how materials, sensors, or accessories can prevent damage or misplacement and extend product lifespan.

3.2.4. Goal 4: Encouraging Sustainable End of Life Management

As shown in Figure 6, Goal 4 seeks to prevent the user from either disposing the product in improper waste channels or keeping it in storage too long. In 2007, only 10% of mobile phones were recycled in the U.S. [64], and in 2010, 11% of all mobile devices (including smartphones, pagers, personal digital assistants, and basic mobile phones) were recycled [65]. Huang and Truong found that consumers prefer to store rather than donate or recycle their obsolete phones because they do not know where to recycle the product or they consider the process of finding a recycling facility to be inconvenient [46], resulting in a steady accumulation of small electronics in basements and attics across the country [66]. As shown in Figure 6, to encourage people to manage the smartphone in a sustainable manner (recycling or reuse), the original packaging can be designed such that it becomes a stand for the device while the product is being used. Then the stand can be converted back into a mailing package so the user can easily and conveniently send the product back to the manufacturer for proper recycling. In parallel, providing greater awareness of recycling services through apps or interface design can combat the widespread challenge consumers face in not knowing where or how to recycle electronic waste.

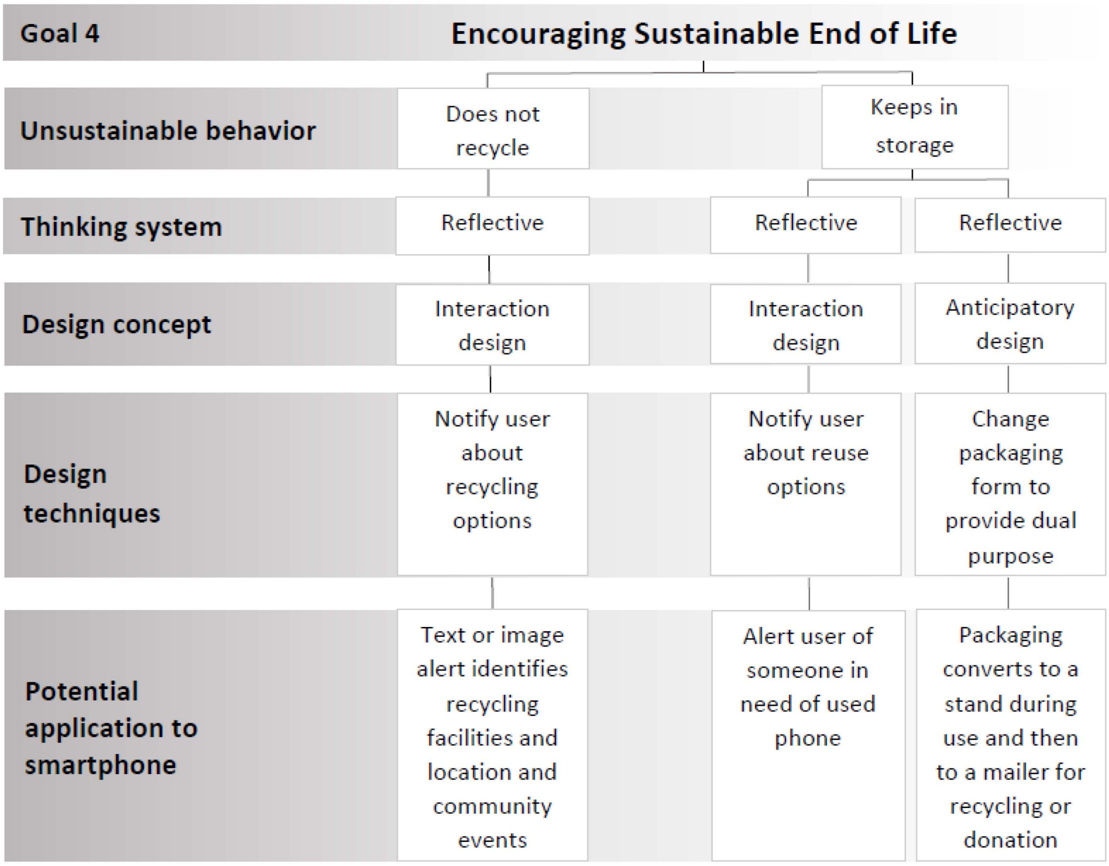

Figure 6. SBD framework applied to meet Goal 4, "Encouraging Sustainable End of Life Management": examples of how to educate or inform users of or encourage participation in recycling or reuse options.

3.3. Smartphone Reimagined with the SBD Framework

Thus far, Figures 3–6 have demonstrated a wide array of individual design techniques inspired by the SBD Framework concepts. However, this framework would ideally lead to integration of design strategies that span both aspects of the human thinking systems and incorporate multiple design techniques for a more holistic outcome. In an industrial product realization process, not all techniques will be feasible, due to competing cost, performance, or brand requirements. However, the framework provides sufficient flexibility to choose among the recommended design techniques. This integration is demonstrated here by reimagining design of a smartphone that meets all four goals and accounts for both aspects of the human thinking system. As shown in Figure 7, some of the potential solutions that have been previously identified in Figures 3–6 are integrated in one comprehensive re-design. Figure 7 represents how a designer could choose among the many techniques that address both aspects of the human thinking system to achieve each design goal. The end result is a modular, easy-to-recycle design that interacts and creates a strong bond with the user.

Four elements of the design solution incorporate reflective thinking and are aligned with all four goals. Goal 1 is achieved with a modular design to allow users to upgrade or change a specific part and extend the product lifespan (Figure 7c). For example, a user can upgrade the phone's camera or replace part of a broken frame by changing one part of the phone rather than the whole frame. Goal 2 educates and makes the user aware of how their current behavior (e.g., battery charging) impacts energy consumption by texting or sending an image notification (Figure 7a). Goal 3 uses sensors within the product to detect distance from the user and send signals that prevent someone from losing their phone (Figure 7b). Goal 4 focuses on packaging design wherein the user is able to transform the original packaging into a stand to hold and charge the phone and to then be used to mail the product back to the manufacturer for recycling at end of life (Figure 7d). The solutions for Goals 1 and 4 (Figure 7b,d) are considered primary because they are directly influenced by the designer, while the solutions for Goals 2 and 3 (Figure 7a,b) are enabling, which means that other specialists (software and app designers) contribute.

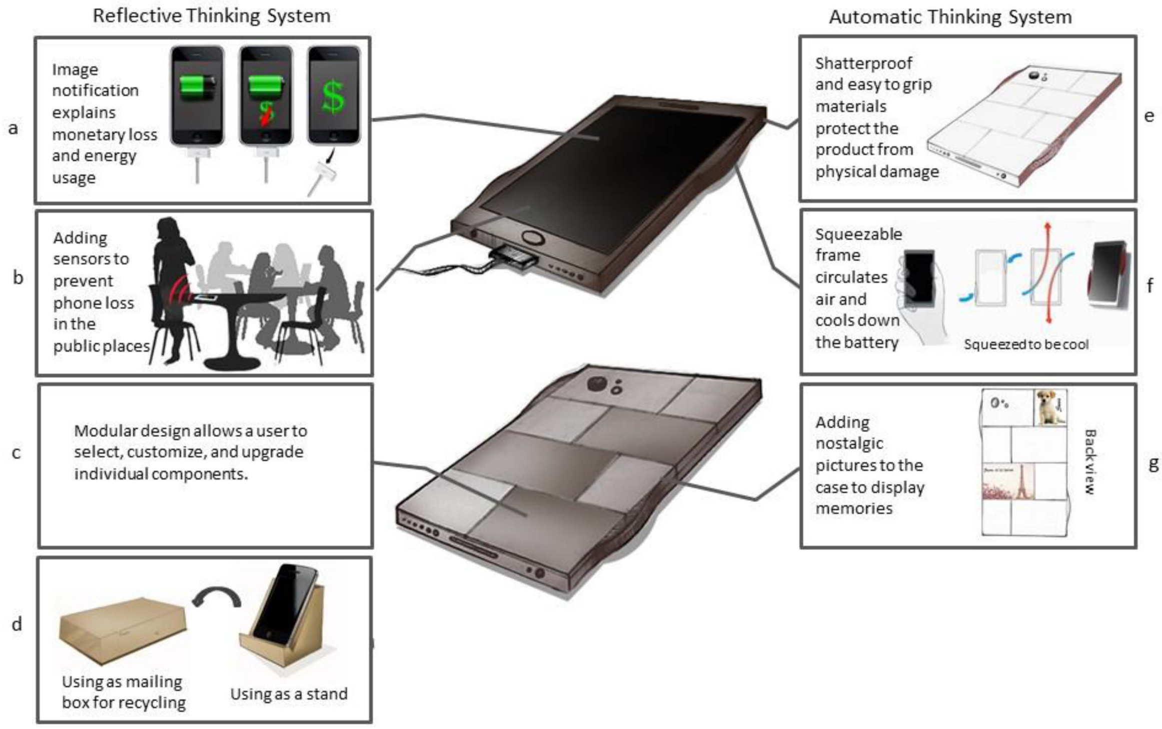

Figure 7. Integrative application of the SBD framework: sustainable smartphone design combines solutions to all four sustainability goals while addressing the reflective (**a–d**) and the automatic (**e–g**) thinking systems.

For automatic thinking, the SBD framework successfully meets three of the four goals. The first goal is achieved by providing the capability to add memorable or nostalgic pictures to the frame to remind users of experiences they had while using the phone (Figure 7g). This concept is intended to create attachment between product and the user, and encourages the user to keep the product longer. A modular form helps the designer apply this concept because the user can add a special image, text or symbol on different pieces of the frame. Goal 2 is achieved by changing the form of the smartphone to balance the temperature when it is exposed to extreme heat (Figure 7f). A frame with small "squeezable" ventable units will circulate air and cool down the battery within the phone, and as a result, cool down the whole device. This design feature helps the battery last longer and consume less energy during usage. After a while, squeezing the phone becomes a habit for the user, resulting in the user becoming more attached to the product. Goal 3 is reached by changing the physical form of the phone by using durable materials (Figure 7e). Shatterproof, slip-proof, or easy to grip materials in the frame will prevent or minimize damage from the phone being dropped.

Because both aspects of how people think have been addressed, the redesigned smartphone results in a product that can potentially last longer and uses less energy. For example, allowing the user to personalize the phone with an image (Goal 1) and using slip proof, durable materials (Goal 3) will prevent damage or dropping and extend the life of the product. Goal 2 designs that aid in cooling down the device and educating the user how to charge properly will prevent the battery from overheating and increase product lifespan. Goal 4 prevents the packaging from being disposed and eliminates the need to purchase a new mailing box. It also makes it more convenient for the user to recycle the smartphone, a consideration currently missing from upgradable phone concepts such as the *Fairphone 2*. While these solutions are by no means the only or optimal set of concepts that would lead to a more environmentally-friendly product, they illustrate how to generate one of many concepts that a designer can evaluate and iterate on before selecting a final concept.

Although many eco-design frameworks conclude with the conceptual design, we propose that some rapid form of validation be included to ensure that the design approach can potentially lead to ultimate environmental benefits. Based on data and assumptions previously reported [14], we considered that applying all of the comprehensive design changes (Figure 7) could extend the product life by up to one year by creating emotional attachment and minimizing risk of dropping and damage and could reduce its annual electricity consumption by 20% through optimized use of the battery [67]. The resultant benefits are estimated to reduce the annualized smartphone cumulative energy demand from 427 MJ/year to 308 MJ/year. By repurposing the packaging material, an additional 3 MJ is saved, due to the avoided demand for packaging required to ship the product back to the manufacturer. In total, these strategies represent a potential 30% reduction in the net impact of producing and using a smartphone. As design decisions are developed and applied, a full scale or even streamlined life cycle assessment would be necessary to fully analyze other environmental benefits. For example, we would estimate that this new design would result in lower material usage impacts from extending the device's lifespan and reduction of uncontrolled releases of toxic substances into the environment since the product packaging is designed to easily send the device to a formal recycling location. However, it may also introduce tradeoffs due to novel material use in surface coatings or added complexity to achieve modular design.

The final design does not include all the solutions identified with the SBD framework. However, these techniques are available options for the designer to combine and apply as needed to meet their goals. The SBD framework allows the designer to look at these solutions holistically, and can be extended to other product sectors with similar design goals.

4. Conclusions

This paper introduced a holistic design approach that addresses both aspects of the human thinking system and enables consumers use electronic products in a more environmentally friendly way. The SBD framework is demonstrated by redesigning a highly demanded and energy intensive consumer electronic, a smartphone, to last longer and have an overall lower energy impact. The SBD framework demonstrates how design plays a critical and direct role in developing products that can be used in a sustainable way. The SBD framework could be further developed to include a more rigorous approach to selecting goals and targeted unsustainable behaviors, as well as to evaluate the new design's performance with other environmental impacts such as material usage. While developed here for consumer electronics, this framework can also be applied to other product systems that have significant environmental impacts across the life cycle, such as commercial or residential appliances.

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