2017

Recommending Sustainable Design Practices by Characterizing Activities And Mindsets

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Abstract: How do designers, engineers, and managers choose the best sustainable design method for their work? How can different design practices combine to complement each other? This study makes recommendations by deconstructing 14 design methods, guides, certifications, and other practices into their constituent activities and mindsets, then characterizing those activities and mindsets. For example, some of the seven activity categories are analysis, ideation, and goal-setting; some of the eight mindset categories are priorities, abstract versus concrete goals, and environmental versus social goals. Recommendations are given for matching sustainable design practices to different usage contexts by their constituent activities and mindsets. It also recommends combining design practices by showing which methods / guides / certifications contain complementary activities or mindsets vs. redundant ones. This work should enable designers and engineers to practice more effective and creative sustainable design.

Keywords: Sustainable design methods, design methodology, design strategy, design activities, design mindsets, The Natural Step, Whole System Mapping, Biomimicry, Life-Cycle Assessment, D4S, Cradle to Cradle, Okala

Reference to this paper should be made as follows: Faludi, Jeremy. (2017) 'Recommending Sustainable Design Methods And Combinations By Characterizing Activities And Mindsets', *Int. J. of Sustainable Design*,.

Biographical notes: Jeremy Faludi, PhD, LEED AP BD+C, is a sustainable design strategist and researcher, specializing in design methods and life-cycle assessment. He is an assistant professor at Dartmouth College, and has taught green product design at Stanford, Minneapolis College of Art and Design, and elsewhere. He holds a PhD in mechanical engineering from University of California, Berkeley, an M.Eng. in product design from Stanford, and a B.A. in physics from Reed College. He co-authored the Autodesk Sustainability Workshop, created the Whole System Mapping design method, designed the prototype of AskNature.org for The Biomimicry Institute, contributed to six books on sustainable design including Worldchanging: A User's Guide for the 21st Century, and a bicycle he helped design appeared in the Smithsonian Cooper-Hewitt Design Museum's 2007 exhibit "Design for the Other 90%".

1 Introduction

Many designers, engineers, and businesspeople attempting to create more sustainable products do so using standard Human-Centred Design while thinking about sustainability issues, not by applying actual sustainable design methods. However, there are dozens of sustainable design methods, guides, certifications, and other practices to choose from. Sustainability is a complex or “wicked” (Rittel and Webber, 1973) problem; as Page showed mathematically (Page, 2014), a diversity of approaches is more effective for solving complex problems than the raw skill of even the brightest individual or best single approach. Yet, time and money inevitably limit the number of approaches used. Which sustainable design practices are best for what context, and how could they integrate with Human-Centred Design or each other? Designers, engineers, and managers should understand what each design practice offers and how to combine multiple practices, or elements thereof, to maximize their value.

Here, "design practice" refers to anything designers do, think, or use, including activities and mindsets and especially combinations thereof. Some of these practices are referred to by their authors as "design methods," (usually ordered collections of activities that depend on each other), some as "design guides" (usually checklists of design principles or goals), some as "certifications" (checklists of accomplishments formally judged by external authorities), or other (such as books or teaching curricula). Nomenclature here follows the originating sources. Sustainable design practices can aim to continue business as usual in less damaging ways, or can aim to persuade users to radically change their lifestyles. While practices studied here could apply to lifestyle change, this paper focuses on product design and production.

Most literature on sustainable design practice either treats all sustainable design the same (Hopkins et al., 2009), (Behrisch et al., 2011), (Molenaar et al., 2010), (Bocken et al., 2014), (DuPont and Wisthoff, 2015) or proposes a specific new design method and studies it (Ameli et al., 2016), (Wisthoff and DuPont, 2016) (Kobayashi, 2006). However, some recommend different design practices for specific circumstances (White et al., 2013), (Jedlicka, 2009), (Thorpe, 2007), (Steffen, 2006), (Lewis et al., 2001). Others categorize sustainable design practices: by their scope and whether they are qualitative or quantitative (Sheldrick and Rahimifard, 2013), (Shedroff, 2009); by the life-cycle stages they address (Telenko et al., 2008), (Oehlberg et al., 2012); or by whether they are design methods, guidelines, checklists, or analytical tools (Knight and Jenkins, 2009). One of the most useful taxonomies is the Living Principles genealogy (Brink et al., 2009), which graphs 31 design practices on axes of "actionable" vs. "visionary" and "selective" vs. "integrated". One of the most extensive studies is Oehlberg's (2012) categorization of 303 principles from 29 different sources by what life-cycle stages they address.

However formally structured these practices may be when taught, in practice professional designers and engineers do not use them as tunnels of process, but as toolboxes. Professionals pull elements from different design methods or design guides opportunistically, often not in order, repeatedly, or skipping steps entirely (Jensen et al., 2010). This is because "undisciplined process" is efficient in time and resources (Cross, 2001). As Homans pointed out, “People who write about methodology often forget that it is a matter of strategy, not of morals. There are neither good nor bad methods, but only methods that are more or less effective under particular circumstances in reaching objectives on the way to a distant goal” (Homans, 1949). Even the canonical prescriber Pahl admitted real practitioners skip steps in practice (Pahl et al., 1999), and Visser found even when engineers say they follow a rigid procedure, they are often opportunistic (Visser, 1990).

Background: Defining Design Activities and Mindsets

There is unfortunately no universally accepted taxonomy of design methods, guides, etc., or the elements comprising them. Here, "design activity" is anything a designer or engineer physically does (e.g., sketch, calculate, model in CAD, etc.) "Design mindset" is anything a designer or engineer mentally considers (e.g., a goal, strategy, paradigm, etc.) Reasons for these definitions follow earlier work (Faludi, 2016) and the following literature:

Engineering design literature has parsed design practices into "activities" (Smith, 1998), (Kudrowitz, 2010), (Vallet et al., 2013) or "techniques" (Hanington and Martin, 2012). Smith (1998) found that 172 ideation practices were all different combinations of 50 core "activities”. Business management literature breaks practices into "toolsets, skillsets, and mindsets" (Horth and Vehar, 2012). This paper uses "activities" rather than "skillsets" because not all activities described here require previous training. Design theorists often do not distinguish between lower-level activities and ordered collections of activities, calling both "methods" (Roschuni et al., 2015), (Roschuni et al., 2011), (Ostergaard and Summers, 2009). Here, "activity" is used where the source does not break down the activity into sub-activities; anything the source describes as a collection of activities and/or mindsets is a "practice".

For mindsets, Badke-Schaub pointed out the importance of shared mental models for successful design processes (Badke-Schaub et al., 2007). Indeed, much literature and training on sustainable design does not propose any specific activities, instead listing goals or strategies to consider while performing design activities (Papanek, 1995), (McDonough and Braungart, 2002), (Hawken et al., 2013), (White et al., 2013). However, terminology is not consistent. While some call them "mindsets" (Horth and Vehar, 2012), (IDEO.org, 2015), others call them "strategies" (De Pauw et al., 2012), (White et al., 2013), (Haemmerle et al., 2012), "guidelines" (Knight and Jenkins, 2009), (Telenko et al., 2008), (Telenko and Seepersad, 2010), or "principles" (Brink et al., 2009), (Oehlberg et al., 2012), (Telenko et al., 2008). Abstract overarching concepts have been called design "paradigms" (Fuad-Luke, 2008), (De Pauw et al., 2010) In this study, the term "mindset" includes all of these variants.

In this paper, the Research Methodology section describes how the design practices studied here were chosen and deconstructed. The Results and Recommendations section lists the constituent activities and mindsets of these design practices, categorizes them, and lists recommendations hypothesized to help practitioners find complementary practices, mix practices to maximize effectiveness, or match different practices to different job roles and stages in the design process. The Limitations section lists gaps and opportunities for future study, and the Conclusion summarizes findings.

2 Research Methodology

Selecting Design Practices

Practices used and recommended by experts were desired for this study. To select practices, literature was reviewed and professional practitioners were interviewed to find practices recommended by experts for their effectiveness. Mentions of design practices were counted, and practices mentioned by more than one source (interviewee or literature) were analysed.

Literature included seven textbooks / handbooks teaching sustainable design and twelve academic studies of sustainable design practices, all cited above in the Introduction's second paragraph. Interviewees included twenty industry professionals and three academics teaching sustainable design. The professionals were designers, engineers, and design managers / executives with a broad range of experience (5 – 35 years) from a broad range of companies: large and small, start-ups and established companies, design consultancies and product manufacturers, in multiple consumer product industries (electronics, apparel, furniture, and telecommunications). They were located in seven US states plus the Netherlands, Germany, Finland, Sweden, Brazil, Israel, Australia, and New Zealand, and were recruited via multiple routes, including the o2 Sustainable Design Network, the Stanford University design alumni mailing list, and alumni of Minneapolis College of Art and Design's master of arts in sustainable design. These interview and literature mentions are listed in Table 1, as well as the primary source citations used to analyse the practices.

Design Practice	Interviews	Literature
Life-Cycle Assessment (Guinée, 2002)	13	7
Cradle to Cradle book (McDonough and Braungart, 2002)	11	7
Biomimicry (Benyus, 1997), (Baumeister et al., 2013)	8	5
The Natural Step (Baxter et al., 2009)	6	5
Human-Centered Design (d.school, 2013), (d.school, 2012)	4	3
Okala Practitioner (White et al., 2013)	4	3
D4S (Crul and Diehl, 2006)	3	1
Whole System Mapping (Faludi, 2015)	3	0
Cradle to Cradle Certification (MBDC, 2012)	2	0
Lunar Field Guide (LUNAR, 2008)	2	2
Living Principles (Brink et al., 2009)	2	1
EPEAT Certification (IEEE, 2009)	0	2
12 Leverage Points (Meadows, 1999)	0	2
Factor Ten Engineering (Lovins et al., 2010)	0	4[1]

Table 1. Number of mentions in interviews and literature. "D4S" is TU Delft's Design for Sustainability; "Lunar Field Guide" is the "Designer's Field Guide to Sustainability" by LUNAR; "EPEAT" is the Electronic Product Environmental Assessment Tool certification.

Table 1 shows the number of times each design practice was mentioned in the 23 interviews and the 10 literature sources. Many other practices not listed in Table 1 were only mentioned once (e.g., Wal-Mart Sustainability Index scorecard, Nike's Making app, permaculture, and others). LEED certification was mentioned more than once but not studied here, as it is intended for architectural design, not product design. The zero literature mentions for Cradle to Cradle Certification and Whole System Mapping are likely due to their release after most sources' publications.

Note the variety in Table 1's practices, including formal sustainable design methods like D4S, design guides like the Lunar Field Guide, product certifications like EPEAT, analysis methods like LCA, etc. The Cradle to Cradle book is more rhetorical persuasion than methodology, but it was

[1] Three of four mentions referred to Factor Ten's predecessor, the book Natural Capitalism (Hawken et al., 2013), since Factor Ten Engineering Principles were released after the publication of most literature sources studied here.

one of the most frequently recommended practices. As mentioned above, Human-Centred Design is not a sustainable design method; however, both expert practitioners and literature recommended it for sustainable design practice because of its useful activities and mindsets (discussed later). Also, its ubiquity makes it useful to see how other practices can relate to it.

Identifying Design Activities and Mindsets

Once the sustainable design practices were selected, literature analysis of Table 1's primary sources deconstructed the practices into activities and mindsets to determine their modularity and uses. For example, Figure 2 is one page of the 25-page D4S worksheet (Crul and Diehl, 2006), with callouts showing activities and mindsets identified.

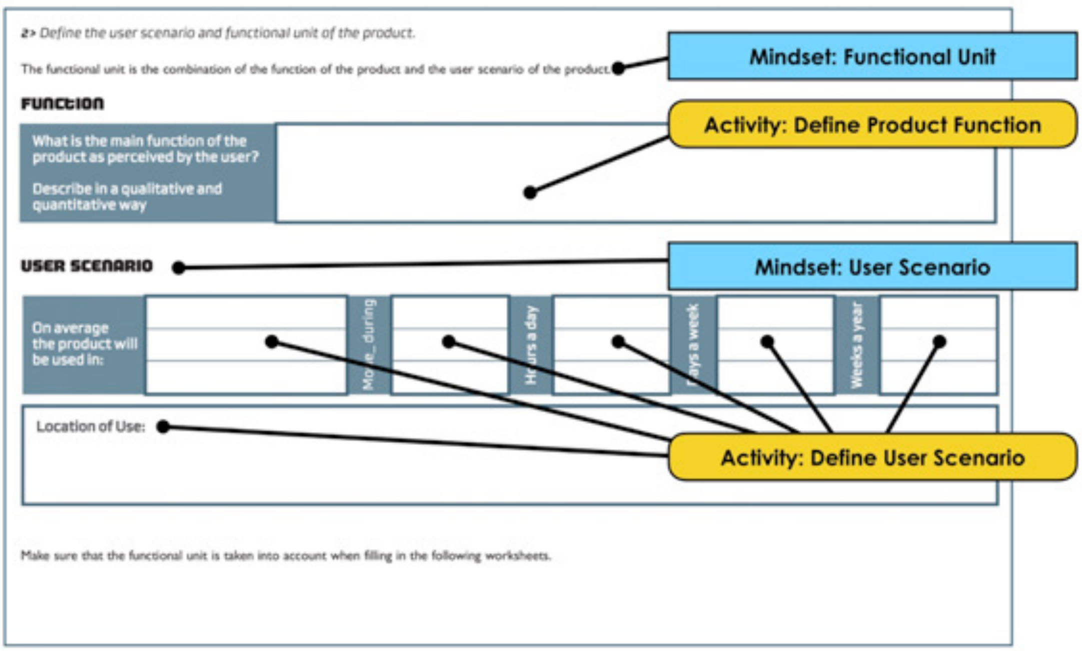


Figure 1. Sample D4S worksheet page with activities and mindsets identified.

Figure 1 identifies two activities and two mindsets: "Define Product Function" and "Define User Scenario" are activities because designers must enact them (fill in the blanks) to determine the functional unit. "Functional Unit" and "User scenario" are mindsets because, once defined here, both concepts are considered during later activities. While it may not seem taxonomically tidy for activities and mindsets to overlap, such overlaps describe real practice. One activity may use multiple mindsets (e.g., The Natural Step's "Awareness" activity uses all four of the "Four Sustainability Principles" mindsets), and one mindset may underlie multiple activities (e.g., The Natural Step's Four Sustainability Principles are used in at least three of its four activities, if not all).

To validate, attempts were made to contact creators of the design practices studied; all creators who responded (Biomimicry, Okala, Living Principles, Whole System Mapping, and Lunar Field Guide) agreed with the analyses or suggested edits that were followed. In addition, a research assistant independently coded activities and mindsets for six (43%) of the design practices, including two design methods, two certifications, and two design guides. Codings agreed with a Cohen's Kappa of .91 overall, .95 for activities and .87 for mindsets.

Analysing Design Activities

Activities were clustered by similarity of purpose. This clustering mostly followed Roschuni's (Roschuni et al., 2015) taxonomy of Research, Analyse, Ideate, Build, and Communicate, similar to but simpler than Vallet's taxonomy (Vallet et al., 2013). Roschuni's "Research" includes data-gathering activities, whether literature or physical or interpersonal. "Analyse" includes making sense of data, quantitatively or qualitatively. "Ideate" includes idea-generation activities. "Build" includes prototyping, physically or virtually. "Communicate" includes presentation of design ideas to others. These categories are useful, but did not capture all clusters of activities found; therefore two additional categories were created, based on Cross (Cross, 2001): Decide and Goal-Setting / Manage. "Decide" includes activities for ranking or choosing ideas to pursue. "Goal-Setting / Manage" includes activities where practitioners define goals for other activities (e.g., writing a design brief, defining the user, or principles such as "Minimize Fasteners"), and includes miscellaneous logistics (e.g., "Discuss Timeframe").

Activities were also analysed to determine how independent they are—activities requiring multiple other activities will be more difficult to mix between one design practice and another. Independence was assessed by a simple question: is this activity impossible to do without a previous activity, not merely improved by it? If not impossible, then the activities' connections were merely considered suggestions.

Analyzing Design Mindsets

Mindsets were clustered by grounded analysis, similar to Brink (2009), Shedroff (2009), Telenko (2008) and Oehlberg (2012). Rather than duplicate efforts such as Oehlberg's and Telenko's categorization by impact in product life-cycle stage, this study clustered mindsets by design-process-related attributes, creating a category when four or more design practices contained a similar mindset. The categories created were: "Systems Thinking" (as opposed to component-by-component thinking), "Checklist" if designers are encouraged to address everything in a list, "Priorities" if designers set priorities rather than address everything, and "Determine Own Goals" or "Predetermined Goals". Predetermined Goals were sub-categorized following Brink, Shedroff, Telenko, and Oehlberg by dividing them into "Environmental" and "Social" goals, as well as "Abstract" and "Concrete" goals.

3 Results and Recommendations

Activities in Sustainable Design Practices

Analysing literature for activities in the fourteen sustainable design practices found that they contained between four and 28 activities. Figures 2 – 4 show examples. For all activities in each design practice, see Appendix A. In these figures, darker boxes are activities; lighter boxes label each activity by category. Black arrows are necessary ordering (the latter step is impossible without the former), and grey arrows are recommended ordering (the former step contributes to the latter, or training materials suggest it). Activity categories are abbreviated R =

Research, A = Analyse, I = Ideate, B = Build, C = Communicate, D = Decide, and G = Goal-Setting / Manage.

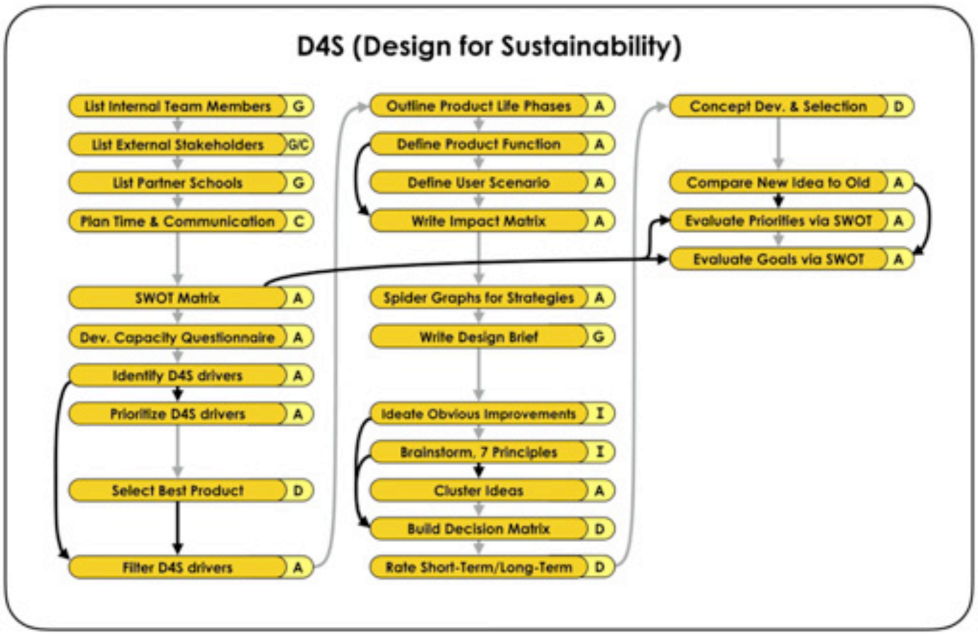


Figure 2. Activities of the D4S method.

Figure 2 shows the results of analysis illustrated in Figure 1. Figure 1's two activities "Define Product Function" and "Define User Scenario" appear in Figure 2, both categorized as Analysis activities, alongside all other activities from the D4S method. Grey arrows into these boxes show that while other activities are recommended to precede these activities, they are not strictly necessary, while the black arrow from Define Product Function shows its output is required to perform the Write Impact Matrix activity. This is because D4S Impact Matrix calculations require the user scenario's "hours a day", "days a week", etc. shown in Figure 1.

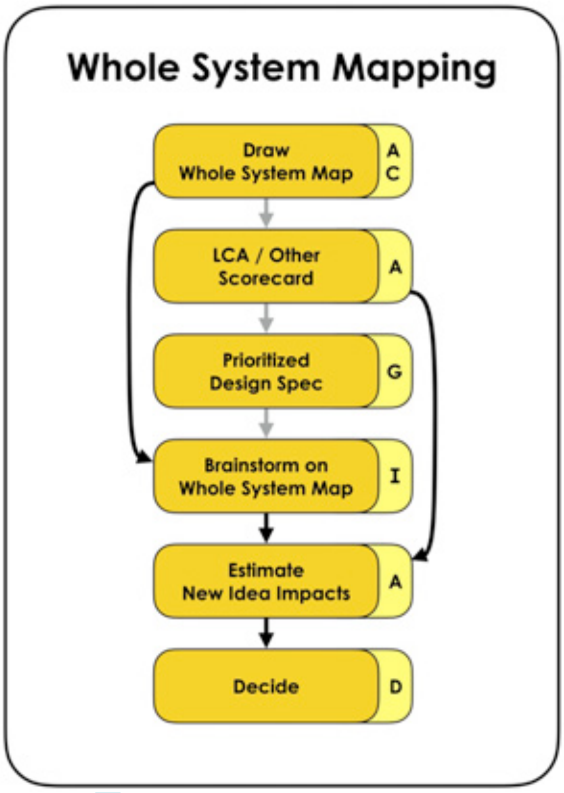


Figure 3. Activities of the Whole System Mapping method.

Figure 3 shows a simpler design method, Whole System Mapping. Note its "Draw Whole System Map" and "Brainstorm on Whole System Map" activities could be performed as a pair without the rest of the method, or mixed into an analysis or ideation phase of another design method, such as The Natural Step. All design guides, certifications, and other practices lack dependencies between their activities (see Appendix A, Figures A7 – A14), so all their activities can be used separately or mixed with other practices.

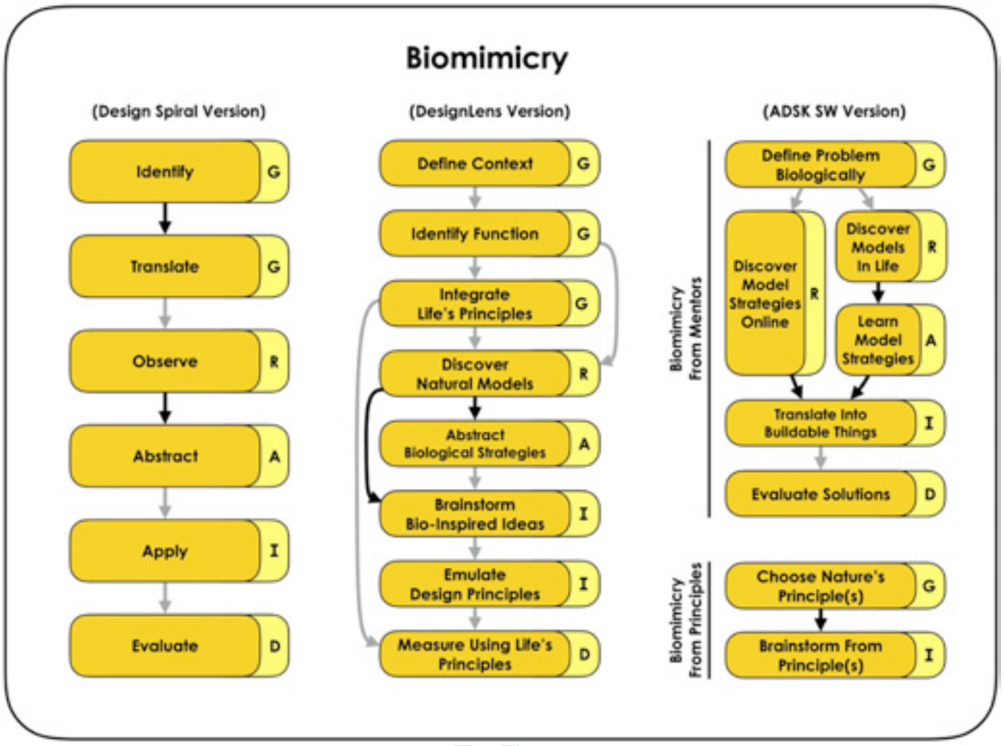


Figure 4. Activities of Biomimicry, for three different versions of the design method.

Figure 4 shows that some design practices have variations; Biomimicry has been taught as a six-step "Design Spiral" (Baumeister et al., 2008), an eight-step "DesignLens" (Baumeister et al., 2013), and the Autodesk Sustainability Workshop ("ADSK SW") version, a four-step process and two-step process that may be used together or separately (Faludi and Menter, 2013); other variations exist as well (Santulli and Langella, 2010). Personal communication with one of the principals at Biomimicry 3.8, source of the Design Spiral and DesignLens, verified that these and other variations exist, with different advantages and disadvantages. These variations contain different activities of different categories (e.g., more Goal-Setting in the DesignLens version), and different dependencies between activities (e.g., no dependence between Nature's Principles and other activities in the ADSK SW version).

Design guides such as the Lunar Field Guide and Living Principles are primarily lists of design considerations (mindsets) not activities; however, goal-related mindsets can be treated as goal-setting activities when designers act to pursue the goals. EPEAT and Cradle to Cradle

Certifications are also primarily lists of goals, though some points require special calculations or factory audits, which must be categorized as Analysis, Research, or others (see Appendix A, Figures A7 and A8).

Reinforcing the hypothesis that designers use design practices as toolboxes, not tunnels, professionals in interviews to select design practices mentioned several design activities individually, not as part of any formal process. These include searching the AskNature.org website (the "Discover Natural Model Strategies" activity in the Biomimicry method), drawing a whole system map (step one of the Whole System Mapping method), brainstorming (an activity in multiple design methods), "Backcasting" (a set of activities from The Natural Step, but not with The Natural Step's specific mindsets), and making a decision matrix (an activity in both Whole System Mapping and D4S). Conversely, interviewees always mentioned LCA as a monolithic entity, not broken into sub-activities.

Recommending Practices Based on Activities

How does classifying activities help designers select the best tool for the job, or the best combination? Table 2 uses the activity categories illustrated in Figures 2 – 4 to show the kinds of activities each practice offers, and where practices' activities are complementary or redundant. Each cell in the table lists the number of activities in that category for that design practice.

Activities were classified into only one category whenever possible. The exception is the Communicate category, which contains several half-values because other activities with different purposes generate communication materials. For example, achieving an eco-label certification such as EPEAT serves as communication to customers, even though it is not an activity in the design practice but a result of the practice; or The Natural Step's list of how a product can fit the Four Sustainability Principles can serve for communication with outside managers or stakeholders. Fractional values for Biomimicry were due to the three variations considered—the numbers of activities in each category were averaged among the three versions shown in Figure 4.

Practice Type	Practice Name	Research	Analysis	Ideation	Build	Communicate	Decision	Goal-Setting / Manage
Traditional Design Method	Human-Centered Design	2	1	1	1	0	0	1
Sustainable Design Methods	D4S	0	14	2	0	2	7	3
	The Natural Step	0	1	1	0	0.5	1	1
	Whole System Mapping	0	3	1	0	0.5	1	1
	Life-Cycle Assessment	1	2	0	0	1	0	1
	Biomimicry	1.33	1	1.66	0	0	1	2.33
Sustainable Design Guides / Certifications / Other	EPEAT Certification	1	0	0	0	10.5	0	40
	Cradle to Cradle Certification	6	7	0	0	0.5	0	14
	Cradle to Cradle book	0	0	0	0	0	0	7
	Okala Practitioner	0	3	1	0	1	1	14
	Lunar Field Guide	0	0	1	0	0	0	14
	Living Principles	0	0	0	0	0	0	21
	12 Leverage Points	0	0	0	0	0	0	12
	Factor Ten Engineering	0	0	0	0	0	0	17

Table 2. Categorization of activities within the design practices. Numeric cells are color-coded by the percent of activities in that category for each practice (darker = higher percent).

As Table 2 shows, no one practice contained activities of all categories. This suggests they could be used together or combined. For example, the only design practice in the table with Build-related activities was Human-Centred Design, the non-sustainability-related design method. This suggests sustainable design practices may not complete the full design cycle, but may require integration with traditional design methods (such as Human-Centred Design). D4S, Whole System Mapping, and LCA contained mostly Analysis activities, while Biomimicry contained more Research, Ideation, and Goal-Setting. The Natural Step was evenly spread among Analysis, Ideation, Decision, and Goal-Setting. D4S contained by far the most activities, but they were largely of the same categories as Whole System mapping and The Natural Step. Human-Centred Design was somewhat evenly spread among Analysis, Ideation, Build, and Goal-Setting, but heaviest on Research (needfinding and user-testing collect data from users). IDEO.org's training materials on Human-Centred Design for sustainable development (IDEO.org, 2015) are less canonical (hence not included in the table) and have similar distribution, but are far more detailed: its 57 activities contained 19 Research, 10 Analysis, 12 Ideation, 9 Build, 5 Communication, 3 Decide, 12 Goal-Setting.

All design guides consisted almost entirely of Goal-Setting. Eco-label certifications were predominantly about Goal-Setting, as expected, but EPEAT Certification contained many Communication activities (e.g., listing recycling code numbers on plastic parts) and Cradle to Cradle Certification contained many Analysis activities (e.g., calculate material reutilization score) and Research activities (e.g., audit factories and identify all material ingredients to 100ppm).

Examining Table 2's columns shows other similarities: Goal-Setting appeared in all methods, certifications, and design guides. Goals (and goal-setting techniques) vary between different practices, but it is clearly a crucial activity category. All practices except LCA contained an Ideation step; this is what separates analysis methods from design methods. All sustainable design methods also contained Decision steps, while LCA and design guides did not. Only D4S and EPEAT contained many Communication activities; one of D4S's strengths is its Communication activities to align executives, the design team, and other stakeholders in their sustainability goals. Perhaps other sustainable design practices could be improved by adding Communication activities.

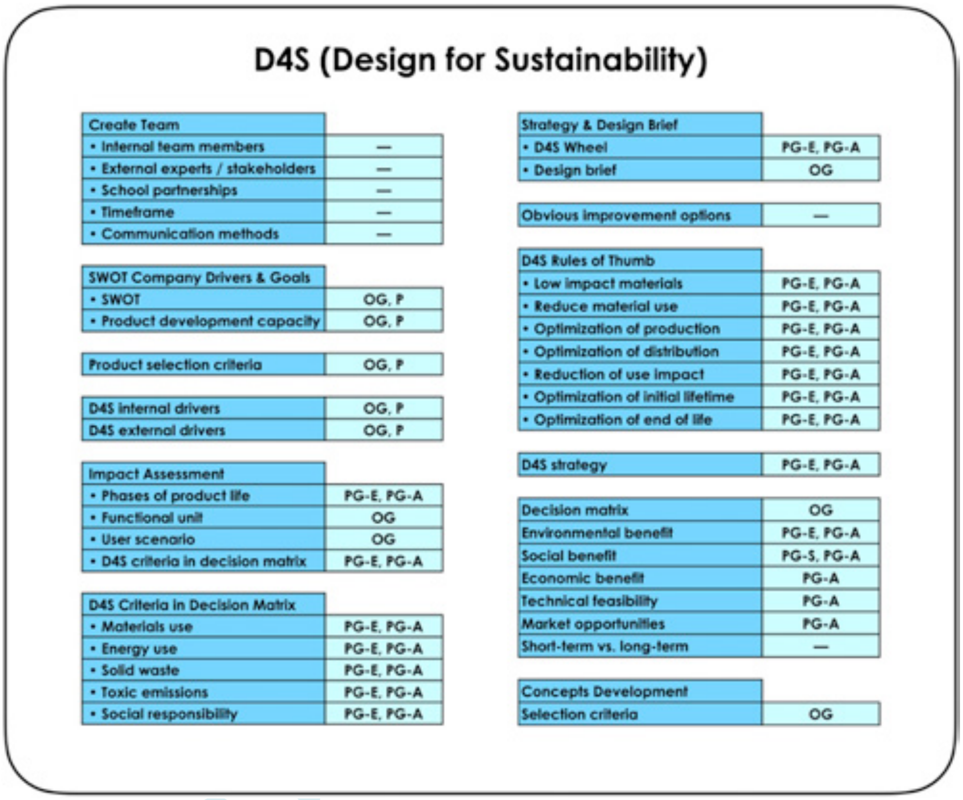
Table 2 suggests certain advantageous combinations of design practices. The Build activity in Human-Centred Design likely complements all sustainable design practices, certifications, and guides. Biomimicry's Research and Ideation activities are likely to complement the many Analysis activities in D4S, Whole System Mapping, and LCA. Goal-Setting activities of different sustainable design guides (e.g., the Living Principles or 12 Leverage Points) likely require Ideation and Research activities to implement them; perhaps generic ones from Human-Centred Design, or sustainability-specific ones from Biomimicry or elsewhere.

In each case, there may be no need to combine whole design practices—individual activities from one practice can be used in another. For example, D4S's Decision Matrix activity may help decide between ideas in Biomimicry, or designers who dislike decision matrices might practice D4S using The Natural Step's "3 Priorities" for decision-making instead. During the interviews to select design practices, some interviewees explicitly mentioned mixing and matching activities: One practised Human-Centred Design with Whole System Mapping's activity "Draw Whole System Map" to guide Human-Centred Design activities. One often searched AskNature.org for biomimetic ideas without Biomimicry's other activities. One used The Natural Step's activity Backcasting but replaced the method's mindsets with ones from the Cradle to Cradle book and elsewhere.

On the other hand, combining design practices with large overlaps may be redundant. EPEAT or Cradle to Cradle Certification and the Lunar Field Guide are unlikely to complement each other, because their activities are nearly all Goal-Setting. Exceptions likely only arise when the mindsets behind Goal-Setting differ, as discussed in the next section.

Mindsets in Sustainable Design Practices

Analysing literature of the selected design practices found that they contained between nine and sixty mindsets. For examples, see Figures 5 and 6; here, darker boxes are mindsets, lighter boxes label them by category where possible. Mindset categories are abbreviated ST = Systems Thinking, C = Checklist, P = Priorities, OG = Determine Own Goals, PG = Predetermined Goals; PG-E = Environmental, PG-S = Social, PG-A = Abstract, and PG-C = Concrete. A dash indicates the mindset does not fit any of these categories. Figures 5 and 6 contain no arrows because mindsets are not performed in order as activities are; instead, related mindsets are grouped together. For all mindsets in each design practice, see Appendix B.



D4S (Design for Sustainability)

Create Team	
• Internal team members	—
• External experts / stakeholders	—
• School partnerships	—
• Timeframe	—
• Communication methods	—
SWOT Company Drivers & Goals	
• SWOT	OG, P
• Product development capacity	OG, P
Product selection criteria	OG, P
D4S internal drivers	OG, P
D4S external drivers	OG, P
Impact Assessment	
• Phases of product life	PG-E, PG-A
• Functional unit	OG
• User scenario	OG
• D4S criteria in decision matrix	PG-E, PG-A
D4S Criteria in Decision Matrix	
• Materials use	PG-E, PG-A
• Energy use	PG-E, PG-A
• Solid waste	PG-E, PG-A
• Toxic emissions	PG-E, PG-A
• Social responsibility	PG-E, PG-A

Strategy & Design Brief	
• D4S Wheel	PG-E, PG-A
• Design brief	OG
Obvious improvement options	—
D4S Rules of Thumb	
• Low impact materials	PG-E, PG-A
• Reduce material use	PG-E, PG-A
• Optimization of production	PG-E, PG-A
• Optimization of distribution	PG-E, PG-A
• Reduction of use impact	PG-E, PG-A
• Optimization of initial lifetime	PG-E, PG-A
• Optimization of end of life	PG-E, PG-A
D4S strategy	PG-E, PG-A
Decision matrix	OG
Environmental benefit	PG-E, PG-A
Social benefit	PG-S, PG-A
Economic benefit	PG-A
Technical feasibility	PG-A
Market opportunities	PG-A
Short-term vs. long-term	—
Concepts Development	
Selection criteria	OG

Figure 5. Mindsets of the D4S method.

Figure 5 shows the results of analysis illustrated in Figure 1. Figure 1's two mindsets "Functional Unit" and "User Scenario" are both categorized as Own Goal in Figure 5 because that worksheet asks designers to define their own values rather than suggesting a goal, such as in D4S's later mindsets "Reduce Material Use", "Select Low Impact Materials", etc. These latter goals are environmentally-focused, not social, so they are categorised PG-E. They are also labelled PG-C because they are more concretely defined than goals such as "Environmental Benefit" and "Social Benefit", classified as abstract.

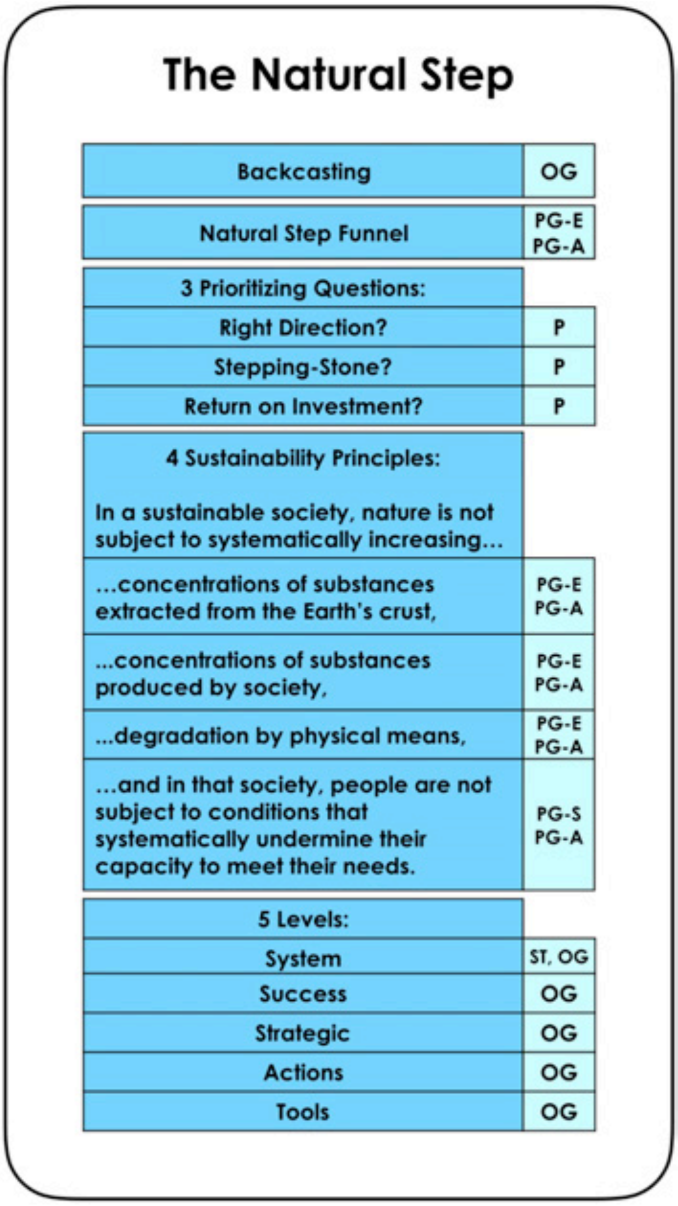


Figure 6. Mindsets of The Natural Step method.

Figure 6 shows mindsets from The Natural Step. Although it and D4S contain different mindsets, there is significant overlap in mindset categories. Each contains mindsets for prioritizing, own goals, and predetermined goals (both environmental and social). One difference between the two practices is that The Natural Step's predetermined goals are all abstract.

Recommending Practices Based on Mindsets

As Table 2 categorized activities for each practice, Table 3 categorizes mindsets for each practice to show what each practice offers, and where they may be complementary or redundant. Details of which mindsets are what category are shown in Figures 5, 6, and Appendix B. Table 3's final column lists mindsets appearing in only one design practice. It does not list numbers of mindsets because, unlike activities, mindsets often fell into multiple categories (e.g., environmental vs. social and abstract vs. concrete), and the number of mindsets did not seem correlated to their importance. For example, biomimicry contains 32 predetermined goals in its list of "Life's Principles", but no interviewees mentioned these, while they did mention biomimicry's core tenet "Nature as Model"; apparently one core mindset can overshadow 32 others.

Practice Name	Systems Thinking	Checklists	Priorities	Determine Own Goals	Predetermined Goals: Environ-mental	Social	Abstract	Concrete	Unique Mindsets
Human-Centered Design				●					• Focus on user needs / values • Embrace experimentation • Iteration
D4S			●	●	●	●	●	●	• Team & project planning • SWOT • Product development capacity • D4S wheel
The Natural Step	●		●	●	●	●	●		• "4 Sustainability Principles" • Backcasting • Natural Step Funnel
Whole System Mapping	●		●	●	●			●	• Visual thinking • Whole system map
Life-Cycle Assessment				●	●			●	• Quantifying sustainability • (13 specific analysis concepts)
Biomimicry				●	●		●	●	• Nature as model • Nature as measure • Nature as mentor • (36 specific design strategies)
EPEAT Certification		●			●			●	• (49 specific design strategies)
Cradle to Cradle Certification		●			●	●		●	• Good, not less bad • Technical nutrients • Biological nutrients • (28 specific design strategies)
Cradle to Cradle Book	●				●	●	●	●	• Good, not less bad • Technical nutrients • Biological nutrients
Okala Practitioner	●		●	●	●	●	●	●	• Ecodesign strategy wheel • Green marketing • (47 specific design strategies)
Lunar Field Guide		●		●	●		●	●	• (15 specific design strategies)
Living Principles	●	●			●	●	●		• Cultural sustainability • (21 specific design concepts)
12 Leverage Points	●			●			●		• Levels of abstraction • (12 specific design strategies)
Factor Ten Engineering	●	●		●	●		●		• Tunneling through the cost barrier • (17 specific design strategies)

Table 3. Categorization of mindsets within the design practices. "Unique mindsets" are those that appear only in that practice. Rows are grouped by traditional design method (Human-Centred Design), sustainable design methods (D4S, etc.), and sustainable design guides / certifications / other.

Table 3 shows some trends by type of design practice. All of the design methods have designers Determine Own Goals, while only half of the certifications, design guides, etc. did. This is sensible, as practitioners generally use design guides to set goals for them. This role for design guides and certifications is also seen in most of them having Checklists, while no design methods do. Some categories are more widely spread across all practices: Systems Thinking, Abstract and Concrete Predetermined Goals, and Predetermined Social Goals. Unsurprisingly, nearly all practices studied contained mindsets of Predetermined Environmental Goals.

Practitioners can use Table 3's category columns to match design practices to their context, such as job role or stage in the design process. For example, practitioners operating at a high level of abstraction (e.g., executives planning product strategy) may choose abstract mindsets, such as in 12 Leverage Points, the Cradle to Cradle book, The Natural Step, or Factor Ten Engineering. Of these, only 12 Leverage Points has the practitioner Determine Own Goals, so it may be preferred by executives who believe they do not need Predetermined Environmental or Social Goals. Designers and engineers implementing details are operating on a concrete level, thus they may choose concrete mindsets, such as in Cradle to Cradle Certification, LCA, or the Lunar Field Guide. Supply chain managers who influence factory working conditions may choose Predetermined Social Goal mindsets such as EPEAT or Cradle to Cradle Certification, not just environmental goals. Engineers and industrial designers can influence the product's physical durability, material choices, etc.; thus, they may prioritize Predetermined Environmental Goals. Okala may be useful to the most job roles, because it contains mindsets of more types than any other practice.

Table 3's last column is also important, as each design practice's unique mindsets may provide key reasons to choose them. For example, designers inspired by direct connection with nature may choose Biomimicry; visually-oriented practitioners may choose Whole System Mapping. Designers in large corporations may be especially sensitive to management buy-in, and thus choose D4S. Graphic designers' marketing and advertising affects cultural norms, thus they may choose the Living Principles.

Design practices can be used in tandem to provide complementary mindsets, just as with activities. For example, design practices with Abstract goals and Concrete goals could be combined to provide guidance throughout the product development process, from strategy to detailed design (e.g., the Natural Step in early stages paired with EPEAT or Cradle to Cradle Certification in later stages). Practices with only Predetermined Environmental Goals, such as LCA, could be complemented by Predetermined Social Goal mindsets such as in the Living Principles.

Also as with activities, practices with similar mindset categories may be redundant. For example, EPEAT and Cradle to Cradle Certification contain almost the same categories of mindsets, so they fulfil almost the same function, just for different product categories (electronics versus housewares or soft goods). However, similarity does not always mean redundancy: Factor Ten Engineering and the Living Principles have nearly identical mindset categories, but their unique mindsets are extremely different, and could complement each other.

In each case, there may be no need to combine whole practices—individual mindsets from one practice can be used in another. For example, as mentioned earlier, one interviewee used Backcasting without The Natural Step's mindset Four Sustainability Principles, instead using mindsets from the Cradle to Cradle book and elsewhere. Whole System Mapping's tutorial video recommends using mindsets from Factor Ten Engineering in its ideation activity to provoke new perspectives.

Combined Recommendations

In addition to recommending mixes of activities and mindsets as described above, many designers, engineers, and managers appreciate recommendations of whole design methods, guides, certifications, etc. Previous authors have recommended these by scope, qualitative versus quantitative, product life-cycle stage, and more. These recommendations are valuable. Rather than duplicate them, this study adds recommendations by job role and stage in the design process.

While any design practice can be useful for any job role, and all roles should come together to practice sustainable design, the activities and mindsets in different practices could give them advantages for different roles. Figure 7 hypothesizes possible advantages, based on the number of activities of each type (Analysis, Ideation, Goal-Setting, etc.) and by types of mindsets present (Checklist, Own Goals, Systems Thinking, etc.) It assumes that on average, engineers favour Analysis, Research, Build, and Concrete Goals; that designers favour Ideation, Research, Build, Checklists, and Concrete Goals; and that managers favour Goal-Setting, Communication, Abstract Goals, and System Thinking.

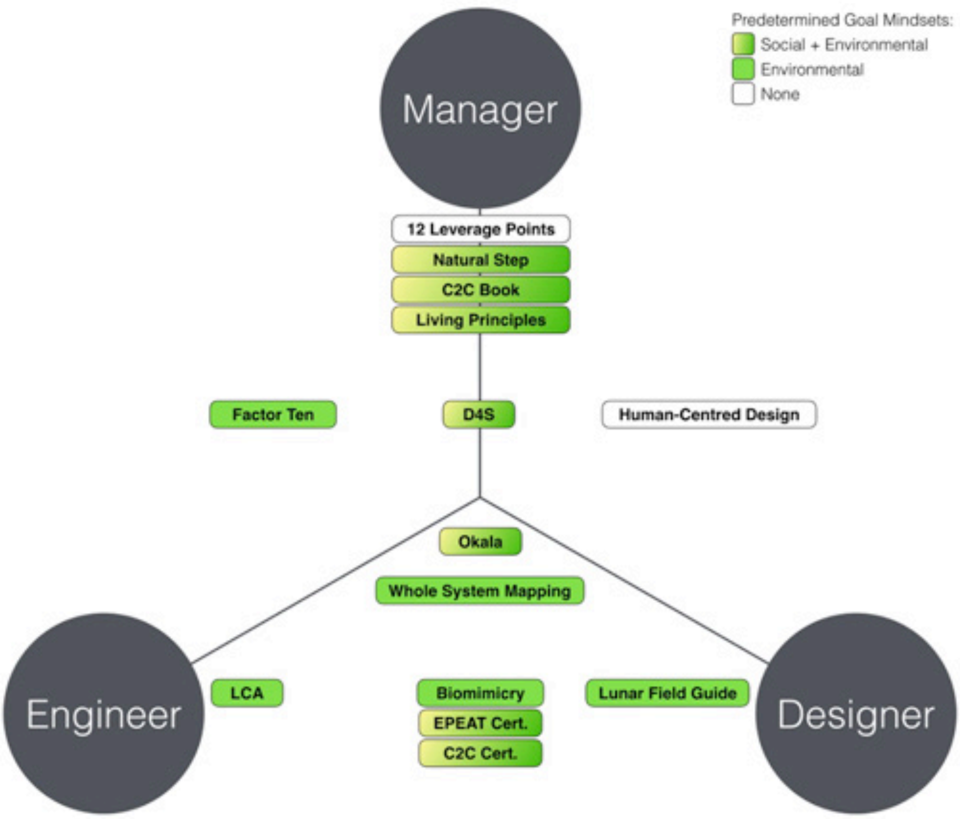


Figure 7. Design practice suggestions by job role.

Colour-coding in Figures 7 and 8 shows Table 3's categories of Predetermined Goal mindsets (Environmental and/or Social). This includes any explicit mention, it does not judge importance. For example, some have categorized the Cradle to Cradle book as only environmental (Shedroff, 2009), (Brink et al., 2009), but Figures 7 and 8 colour it both social and environmental because its mindset "Respect Diversity" (chapter 5) includes social considerations. Conversely, 12 Leverage Points is often used for both environmental and social benefit, but is coloured white because it does not contain Predetermined Goal mindsets explicitly suggesting social or environmental targets.

Figure 7 suggests that LCA may be preferred by engineers, Natural Step by managers, and Lunar Field Guide by designers. Biomimicry, EPEAT, and Cradle to Cradle Certification may balance between engineers and designers because of their many Predetermined Concrete Goals. Factor Ten may balance between engineers and managers because while its goals are Abstract, several are quantitative. D4S and Whole System Mapping are near the centre because they contain mixes of Concrete and Abstract, Analysis and Ideation; D4S's business-oriented mindsets such as SWOT and product development capacity pull it toward managers, while Whole System Mapping's use of LCA and visual mapping pull it towards engineers and designers. Okala may be the most universal due to its balance of Predetermined Concrete Goals, Abstract Goals, and Own Goals. Empirical studies could test these hypothesized suggestions.

Usage may vary not only by job role but by team role. Design teams who can only bill for traditional design activities, not sustainability-specific analysis or research, may be confined to using Goal-Setting mindsets from the Lunar Field Guide, Living Principles, Okala, Cradle to Cradle book, or others. By contrast, design teams with more control over their time could use design practices requiring significant Analysis or Research, such as D4S, LCA, Whole System Mapping, and Biomimicry.

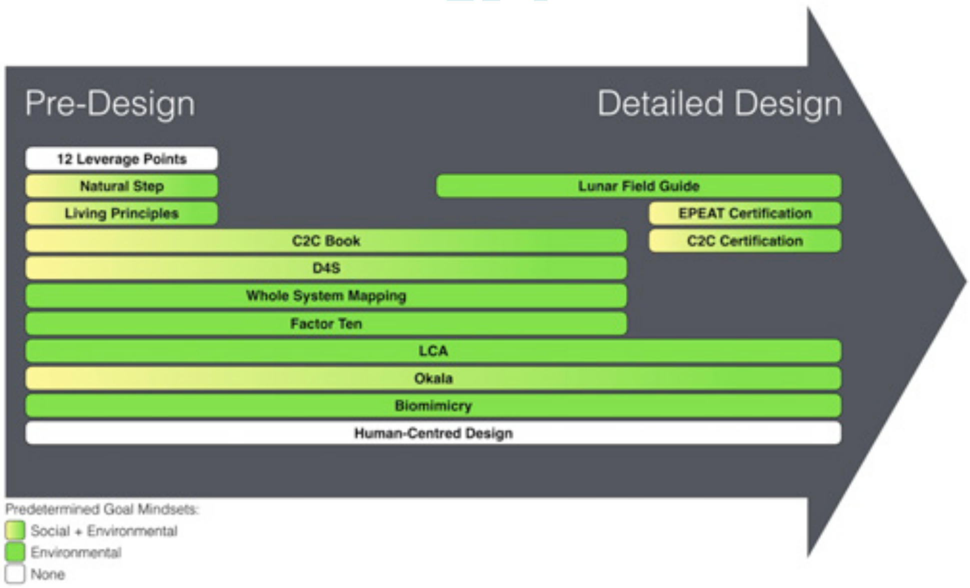


Figure 8. Design practice suggestions by time in design process

While any design practice can be useful at any time in the design process, and sustainable design should infuse the whole design process, the activities and mindsets of different practices may provide advantages at different times in the design process. Figure 8 hypothesizes recommendations assuming Predetermined Abstract Goals, Priorities, Systems Thinking, and Research favour pre-design, while Predetermined Concrete Goals and Build favour detailed design. Practices containing multiple types span multiple design stages. Given these assumptions, highly Abstract and Systems Thinking-oriented practices such as 12 Leverage Points may be best for pre-design, while highly Concrete practices such as EPEAT and Cradle to Cradle Certification may be best in detailed design. Mixed practices such as Okala may be similarly useful at different design stages, or throughout. An exception, Factor Ten stretches past pre-design because although it contains only Abstract Predetermined Goals, some are highly detail-oriented, thus they may require more detailed design stages. As mentioned previously, this analysis may suggest combinations of design practices (e.g., The Natural Step in early stages paired with EPEAT or Cradle to Cradle Certification later.) Empirical studies could test these hypothesized suggestions.

4 Limitations

This study was limited to identifying and classifying activities and mindsets within design practices; as mentioned above, it does not judge which are most important in each practice. It invites empirical research into what activities and mindsets are valued most by designers, engineers, and managers. Such studies would greatly inform which activities and mindsets are recommended, and what combinations are recommended for whom and when. In addition, empirical studies should test mixing and matching of elements from different design practices in different contexts. Empirical studies would also be useful to test the matching of design practices to job roles and stages in the design process hypothesized in Figures 7 and 8. Finally, tools (software or physical) for sustainable design were not studied here, but can greatly change the effectiveness of some activities (e.g., LCA software versus lookup tables).

5 Conclusion

How can designers, engineers, and managers improve sustainable design practice, and integrate it with status-quo design practices such as Human-Centred Design? Practitioners will continue using different methods for different contexts, or opportunistically combining components from different practices. To save them the trouble of personally experimenting with thousands of combinations of components, and to help them think more critically about their mixing and matching, this study examined fourteen expert-recommended design methods, guides, certifications, and other practices. It deconstructed the design practices into their component activities and mindsets, then categorized those components to help practitioners mix and match activities and mindsets to fit the job at hand.

Results found many differences and similarities in the types of activities and mindsets in different design practices. For example, some sustainable design methods contained mostly Analysis activities, while certifications and design guides contained mostly Goal-Setting activities; some design practices contained only Abstract Predetermined Goals while others contained Concrete Predetermined Goals or helped designers set their Own Goals. Design practices with significantly different categories of activities and mindsets are likely to complement each other (e.g., a laptop designer might pull a computer-specific Predetermined Goal mindset from EPEAT Certification to help guide the Goal-Setting or Ideation activities in The Natural Step method). Conversely, design practices with large overlaps in activity or mindset categories may be redundant. See Tables 2 and 3 and surrounding text for suggestions hypothesized from these categorizations. For categorizations of each specific activity and mindset in each design practice, see Appendices A and B. Readers may also add more design practices not analysed here by following this study's deconstruction and categorization schemes. Finally, these categorizations were used to hypothesize recommendations of different design practices for different job roles (designer, engineer, or manager) in Figure 7 and for different stages in the design process in Figure 8. As mentioned in Limitations, the hypothesized recommendations listed in Results should be tested with designers, engineers, and managers to see which activities and mindsets they most value from each design practice, and why they value them. Such information would greatly affect recommendations.

These results should complement previous categorizations of sustainable design practices. Telenko's (2008) and Oehlberg's (2012) categorizations of sustainable design mindsets by product life-cycle stage are complemented by the hypothesized recommendations of design practices by job role and stage in design process, and vice-versa. For example, designers seeking to apply The Natural Step to transportation could use Oehlberg's list of transportation-stage mindsets to guide Backcasting activities. These results should also complement Brink's (2009) and Shedroff's (2009) categorizations, as Abstract Goals versus Concrete Goals are similar to Brink's (2009) "actionable" versus "visionary", but the additional factors analysed here help practitioners choose using more variables (e.g. mindsets for Own Goals, Checklists, Priorities, and all the activity categories). Shedroff's (2009) categorizations of design practices into environmental, social, and economic relevance, as well as Brink's addition of cultural relevance, are more detailed than those here, and would complement these recommendations. The primary value of this analysis is likely the breakdown of different design practices into their activities and mindsets in Tables 2 and 3, to facilitate mixing and matching by practitioners.

Besides the recommendations hypothesized in Results, it is hoped this study can help designers, engineers, and team leaders think more critically about the design activities and mindsets they use to drive sustainability, and experiment with new combinations to design better. Such exploration could lead to new sustainable design methods for specific circumstances, or perhaps even universally improve sustainable design practice.

6 Acknowledgments

Thanks to Alice Agogino, Sara Beckman, Alastair Iles, Laura Driscoll, and Avary Kent for their feedback. This work was partially funded through US National Science Foundation Integrative Graduate Education and Research Traineeship grant #1144885.

References

Ameli, M., Mansour, S., Ahmadi-Javid, A., 2016. A sustainable method for optimizing product design with trade-off between life cycle cost and environmental impact. Environ Dev Sustain 1–14. doi:10.1007/s10668-016-9864-x

Badke-Schaub, P., Neumann, A., Lauche, K., Mohammed, S., 2007. Mental models in design teams: a valid approach to performance in design collaboration? CoDesign 3, 5–20.

Baumeister, D., Tocke, R., Dwyer, J., Ritter, S., Benyus, J., 2013. Biomimicry Resource Handbook: A Seed Bank of Best Practices, 2013 Edition. Biomimicry 3.8, Missoula, MT.

Baumeister, D., Tocke, R., Dwyer, J., Ritter, S., Benyus, J., 2008. Biomimicry Resource Handbook: A Seed Bank of Best Practices, 2008 Edition. Biomimicry 3.8, Missoula, MT.

Baxter, K., Boisvert, A., Lindberg, C., Mackrael, K., 2009. Sustainability Primer: Step By Natural Step. The Natural Step Canada.

Behrisch, J., Ramirez, M., Giurco, D., 2011. Ecodesign report: results of a survey amongst Australian industrial design consultancies [WWW Document]. URL https://www.academia.edu/2764803/Ecodesign_report_results_of_a_survey_amongst_Australian_industrial_design_consultancies (accessed 5.11.15).

Benyus, J.M., 1997. Biomimicry. William Morrow New York.

Bocken, N.M.P., Farracho, M., Bosworth, R., Kemp, R., 2014. The front-end of eco-innovation for eco-innovative small and medium sized companies. Journal of Engineering and Technology Management 31, 43–57.

Brink, G., Destandau, N., Hamlett, P., 2009. Genealogy of the Living Principles. AIGA Center for Sustainable Design.

Cross, N., 2001. Design cognition: Results from protocol and other empirical studies of design activity.

Crul, M.R.M., Diehl, J.C., 2006. Design for Sustainability: A practical approach for developing economies. UNEP/Earthprint.

De Pauw, I.C., Karana, E., Kandachar, P.V., 2012. Nature-inspired design strategies in sustainable product development: A case study of student projects, in: DESIGN 2012: 12th International Conference on Design, Dubrovnik, Croatia, 21-24 May 2012. Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. The Design Society, Glasgow.

De Pauw, I., Kandachar, P., Karana, E., Peck, D., Wever, R., 2010. Nature inspired design: Strategies towards sustainability, in: Knowledge Collaboration & Learning for Sustainable Innovation: 14th European Roundtable on Sustainable Consumption and Production (ERSCP) Conference and the 6th Environmental Management for Sustainable Universities (EMSU) Conference, Delft, The Netherlands, October 25-29, 2010. Delft University of Technology; The Hague University of Applied Sciences; TNO.
d.school, 2013. Bootcamp Bootleg. Hasso Platner Institute of Design at Stanford University.
d.school, 2012. An Introduction to Design Thinking: Facilitator's Guide. Hasso Platner Institute of Design at Stanford University.
DuPont, B., Wisthoff, A., 2015. Exploring The Retention Of Sustainable Design Principles In Engineering Practice Through Design Education, in: Proceedings of the ASME 2015 International Design Engineering Technical Conferences. Presented at the ASME IDETC, Boston, MA.
Faludi, J., 2016. Differentiating Sustainable Design Methods: What Activities or Mindsets Are Universal, What Are Unique? Presented at the Sustainable Innovation 2016, Epsom, UK.
Faludi, J., 2015. A Sustainable Design Method Acting as an Innovation Tool, in: ICoRD'15–Research into Design Across Boundaries Volume 2. Springer, pp. 201–212.
Faludi, J., Menter, A., 2013. Product Design: Biomimicry [WWW Document]. Autodesk Sustainability Workshop. URL http://sustainabilityworkshop.autodesk.com/products/biomimicry (accessed 7.21.16).
Fuad-Luke, A., 2008. Slow design, in: Design Dictionary. Springer, pp. 361–363.
Guinée, J.B., 2002. Handbook on life cycle assessment operational guide to the ISO standards. The international journal of life cycle assessment 7, 311–313.
Haemmerle, L., Shekar, A., Walker, D., 2012. Key concepts of radical innovation for sustainability, with complementary roles for industrial design and engineering. International Journal of Sustainable Design 2, 24–45.
Hanington, B., Martin, B., 2012. Universal methods of design: 100 ways to research complex problems, develop innovative ideas, and design effective solutions. Rockport Publishers.

Hawken, P., Lovins, A.B., Lovins, L.H., 2013. Natural capitalism: The next industrial revolution. Routledge.
Homans, G.C., 1949. The strategy of industrial sociology. American Journal of Sociology 330–337.
Hopkins, M.S., Townend, A., Khayat, Z., Balagopal, B., Reeves, M., Berns, M., 2009. The business of sustainability: what it means to managers now. MIT Sloan Management Review 51, 20.
Horth, D.M., Vehar, J., 2012. Becoming a leader who fosters innovation. Greensboro, NC: Center for Creative Leadership.
IDEO.org, 2015. Design Kit: The Field Guide to Human-Centered Design.
IEEE, 2009. Electronic Product Environmental Assessment Tool (EPEAT). IEEE 1680-2009 Standard for Environmental Assessment of Electronic Products. Green Electronics Council.
Jedlicka, W., 2009. Packaging sustainability: tools, systems and strategies for innovative package design. John Wiley & Sons.
Jensen, T.E., Andreasen, M.M., others, 2010. DESIGN METHODS IN PRACTICE-BEYOND THE'SYSTEMATIC APPROACH'OF PAHL & BEITZ, in: DS 60: Proceedings of DESIGN 2010, the 11th International Design Conference, Dubrovnik, Croatia.
Knight, P., Jenkins, J.O., 2009. Adopting and applying eco-design techniques: a practitioners perspective. Journal of Cleaner Production 17, 549–558. doi:10.1016/j.jclepro.2008.10.002
Kobayashi, H., 2006. A systematic approach to eco-innovative product design based on life cycle planning. Advanced engineering informatics 20, 113–125.
Kudrowitz, B.M., 2010. Haha and aha!: Creativity, idea generation, improvisational humor, and product design. Massachusetts Institute of Technology.
Lewis, H., Gertsakis, J., Grant, T., Morelli, N., Sweatman, A., 2001. Design + Environment. London: Greenleaf.
Lovins, A., Bendewald, M., Kinsley, M., Bony, L., Hutchinson, H., Pradhan, A., Sheikh, I., 2010. Factor ten engineering design principles. Rocky Mountain Institute.
LUNAR, 2008. The Designer's Field Guide to Sustainability. LUNAR Design.
MBDC, L., 2012. Overview of the Cradle to Cradle Certified Product Standard, Version 3.0. McDonough Braungart Design Chemistry, LLC.
McDonough, W., Braungart, M., 2002. Cradle to cradle: Remaking the way we make things. MacMillan.

Meadows, D.H., 1999. Leverage points: Places to intervene in a system. Sustainability Institute Hartland, VT.
Molenaar, N., Keskin, D., Diehl, J.C., Lauche, K., 2010. Innovation process and needs of sustainability driven small firms, in: Knowledge Collaboration & Learning for Sustainable Innovation: ERSCP-EMSU Conference, 25-29 October 2010, Delft, The Netherlands.
Oehlberg, L., Bayley, C., Hartman, C., Agogino, A., 2012. Mapping the Life Cycle Analysis and Sustainability Impact of Design for Environment Principles, in: Leveraging Technology for a Sustainable World. Springer, pp. 221–226.
Ostergaard, K.J., Summers, J.D., 2009. Development of a systematic classification and taxonomy of collaborative design activities. Journal of Engineering Design 20, 57–81.
Page, S.E., 2014. Where diversity comes from and why it matters? European Journal of Social Psychology 44, 267–279.
Pahl, G., Badke-Schaub, P., Frankenberger, E., 1999. Resume of 12 years interdisciplinary empirical studies of engineering design in Germany. Design Studies 20, 481–494.
Papanek, V., 1995. The green imperative: Natural design for the real world. Thames and Hudson.
Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci 4, 155–169. doi:10.1007/BF01405730
Roschuni, C., Agogino, A.M., Beckman, S.L., others, 2011. The DesignExchange: Supporting the design community of practice, in: DS 68-8: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 8: Design Education, Lyngby/Copenhagen, Denmark, 15.-19.08. 2011.
Roschuni, C., Kramer, J., Agogino, A., 2015. Design Talking: How Design Practitioners Talk About Design Research Methods, in: ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, pp. V003T04A027–V003T04A027.
Santulli, C., Langella, C., 2010. Hybridisation between technology and biology in design for sustainability. International Journal of Sustainable Design 1, 293–304.
Shedroff, N., 2009. Design is the problem: the future of design must be sustainable. Rosenfeld Media.

Sheldrick, L., Rahimifard, S., 2013. Evolution in Ecodesign and Sustainable Design Methodologies, in: Nee, A.Y.C., Song, B., Ong, S.-K. (Eds.), Re-Engineering Manufacturing for Sustainability. Springer Singapore, pp. 35–40.
Smith, G.F., 1998. Idea-generation techniques: a formulary of active ingredients. The Journal of Creative Behavior 32, 107–134.
Steffen, A., 2006. Worldchanging: A User's Guide for the 21st Century, Abrams. Inc: NY.
Telenko, C., Seepersad, C.C., 2010. A methodology for identifying environmentally conscious guidelines for product design. Journal of Mechanical Design 132, 091009.
Telenko, C., Seepersad, C.C., Webber, M.E., 2008. A compilation of design for environment principles and guidelines, in: ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, pp. 289–301.
Thorpe, A., 2007. The designer's atlas of sustainability. Island Press.
Vallet, F., Eynard, B., Millet, D., Mahut, S.G., Tyl, B., Bertoluci, G., 2013. Using eco-design tools: An overview of experts' practices. Design Studies 34, 345–377. doi:10.1016/j.destud.2012.10.001
Visser, W., 1990. More or less following a plan during design: opportunistic deviations in specification. International journal of man-machine studies 33, 247–278.
White, P., Belletire, S., Pierre, L.S., 2013. Okala Practitioner: Integrating Ecological Design. IDSA.
Wisthoff, A., DuPont, B., 2016. A Method for Understanding Sustainable Design Trade-Offs During the Early Design Phase, in: Sustainable Design and Manufacturing 2016. Springer, Cham, pp. 271–280.

Appendix A: Activities in All Design Practices

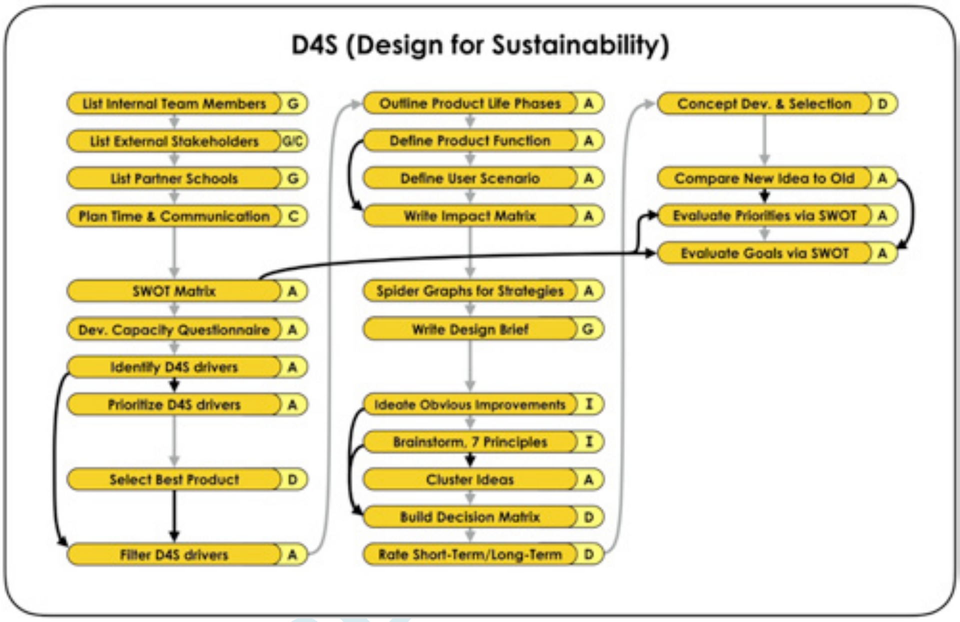


Figure A1. Activities of D4S.

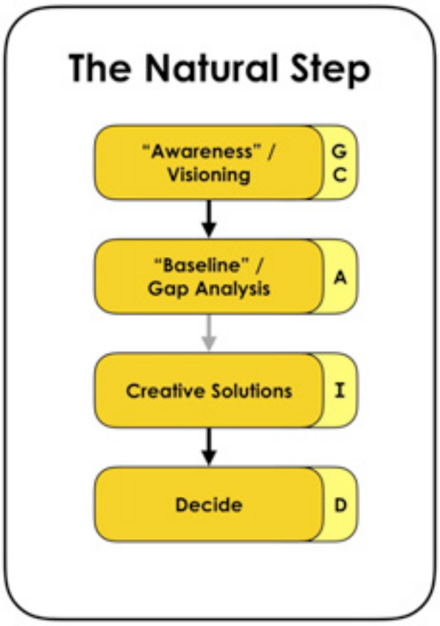


Figure A2. Activities of The Natural Step.

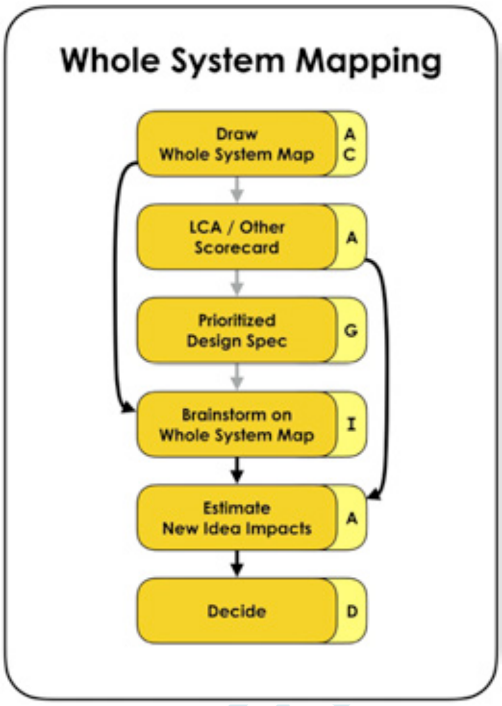


Figure A3. Activities of Whole System Mapping.

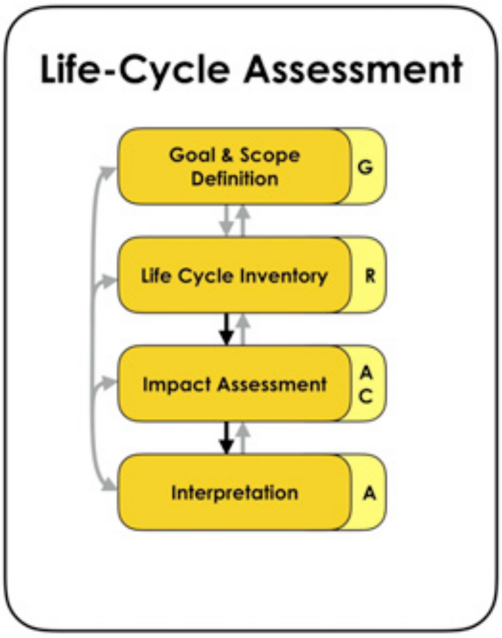


Figure A4. Activities of Life-Cycle Assessment.

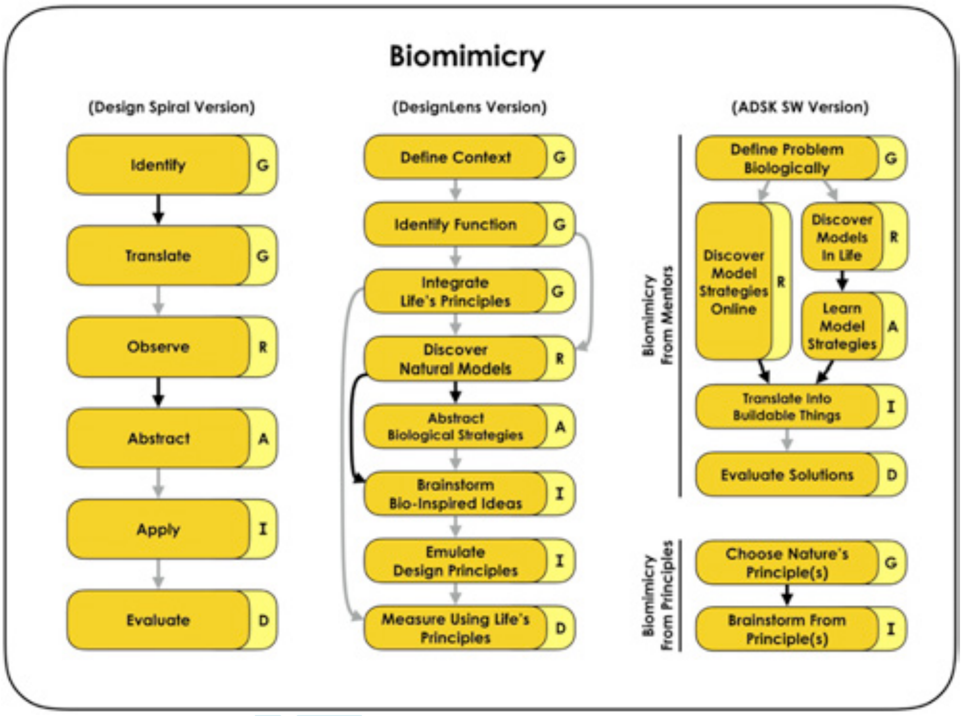


Figure A5. Activities of Biomimicry (3 versions, see main text for descriptions).

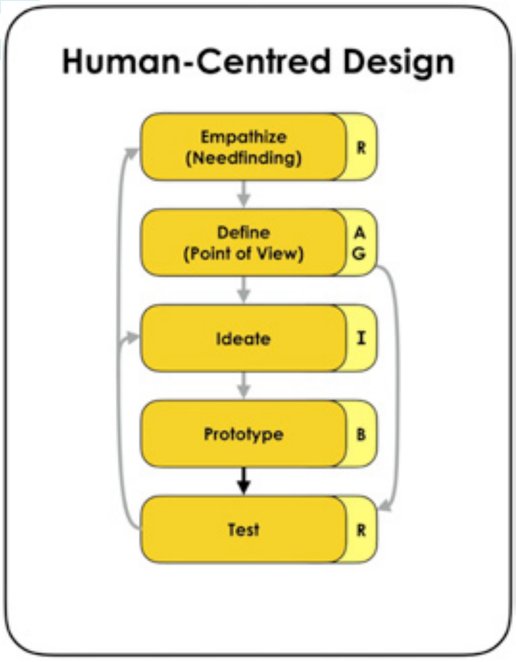


Figure A6. Activities of Human-Centred Design.

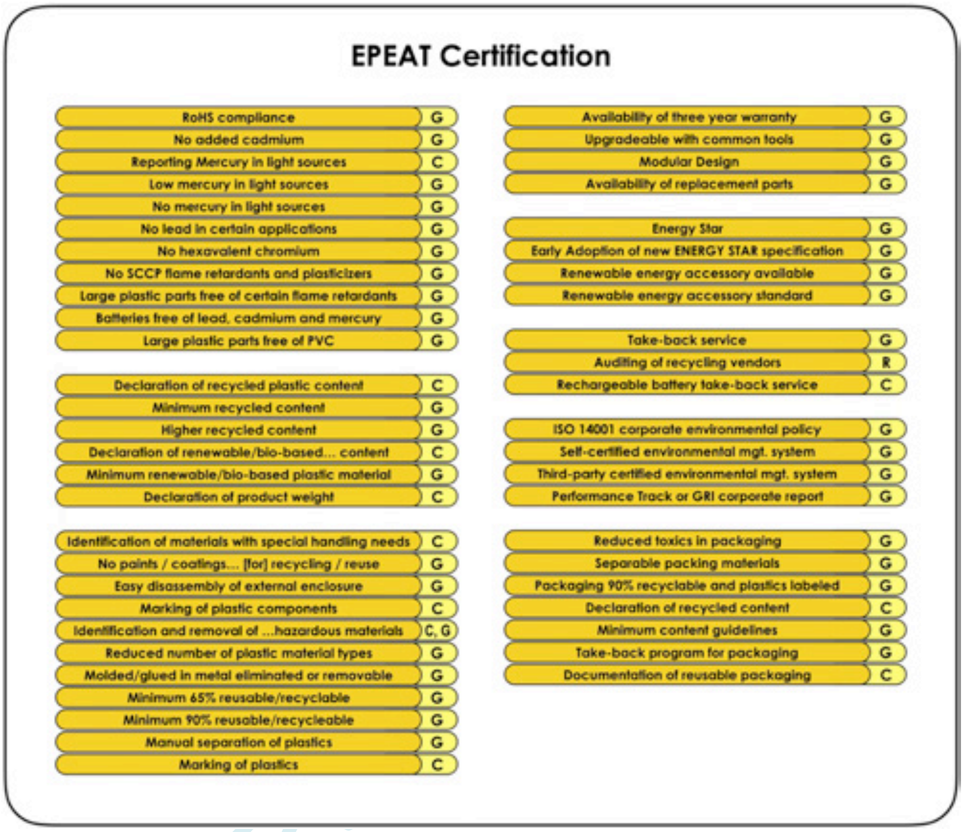


Figure A7. Activities of EPEAT Certification.

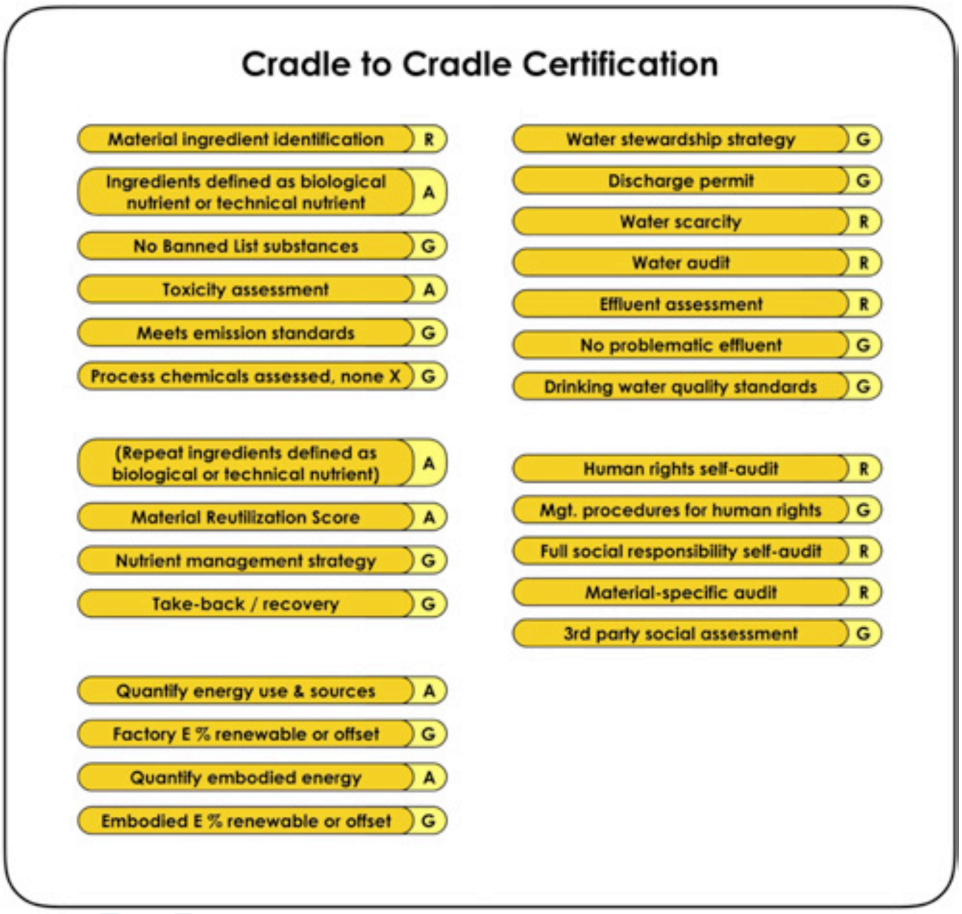


Figure A8. Activities of Cradle to Cradle Certification.

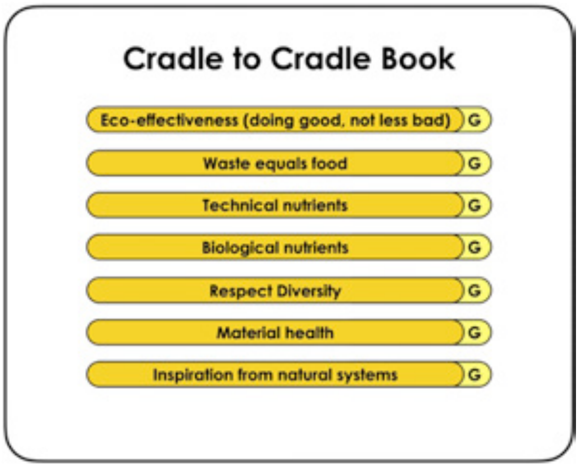


Figure A9. Activities of the Cradle to Cradle book.

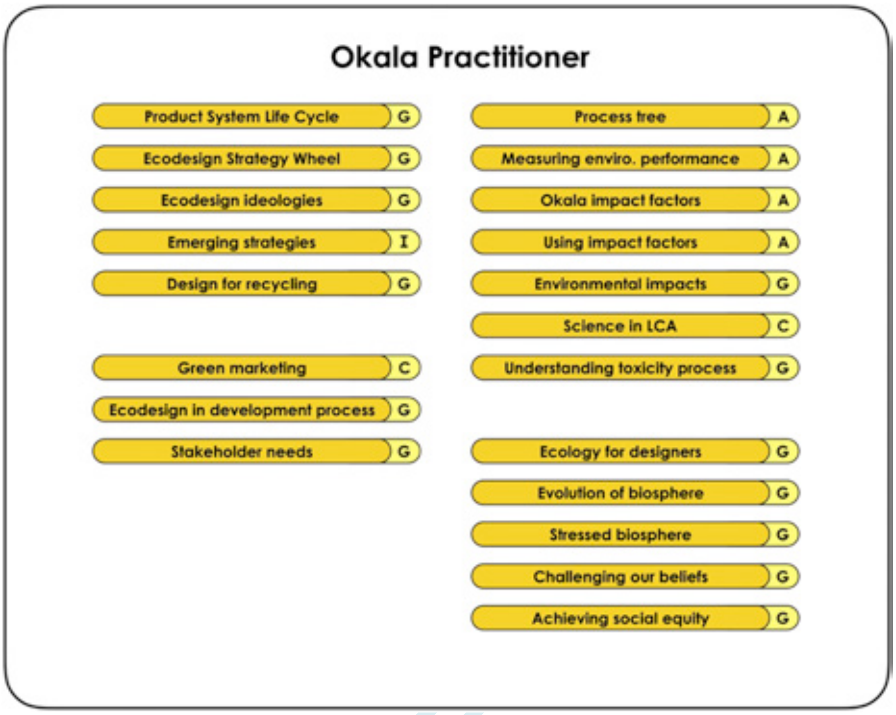


Figure A10. Activities of Okala Practitioner.

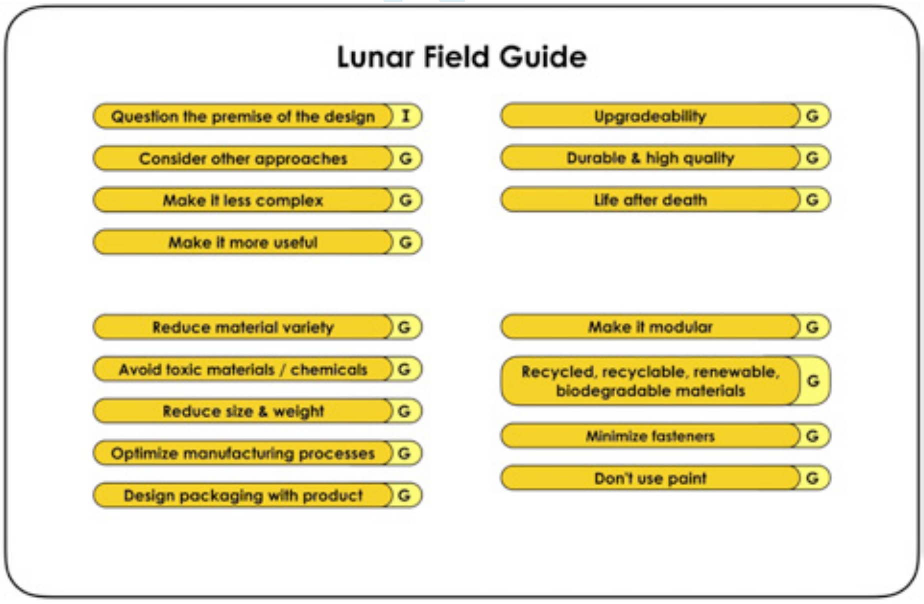


Figure A11. Activities of the Lunar Field Guide.

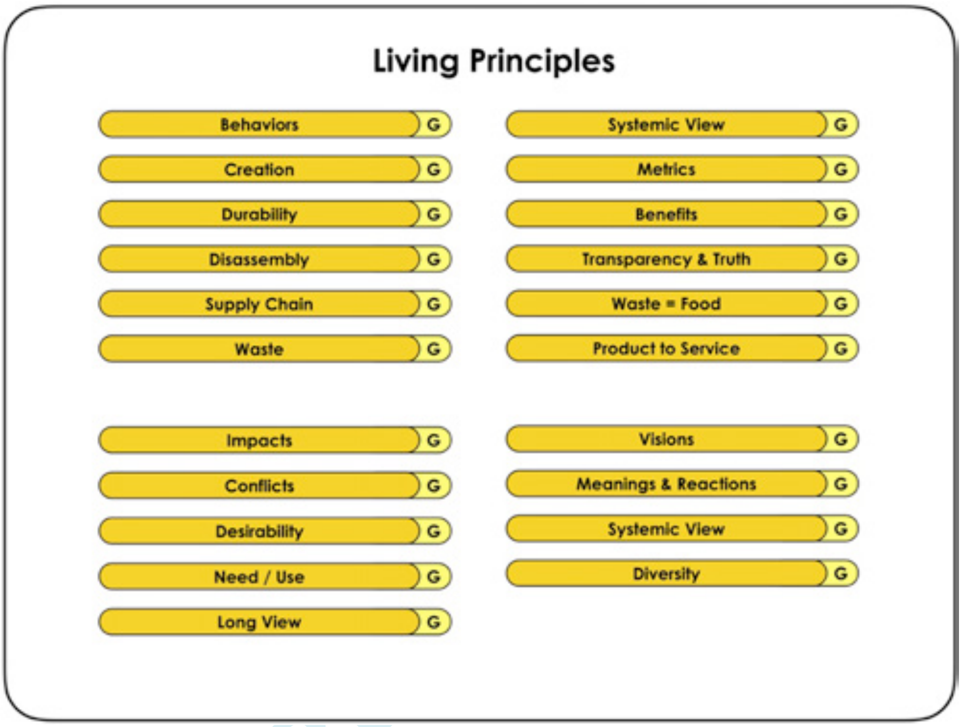


Figure A12. Activities of Living Principles.

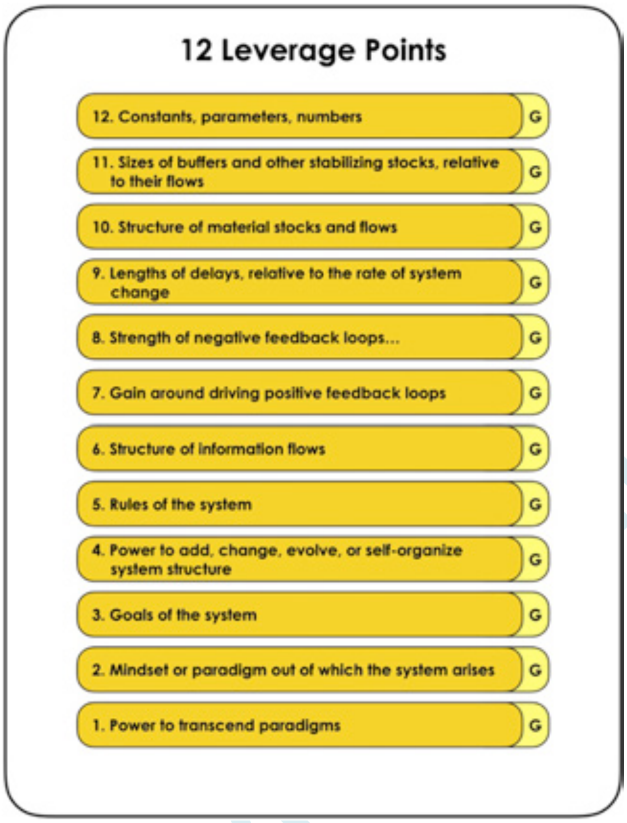


Figure A13. Activities of 12 Leverage Points.

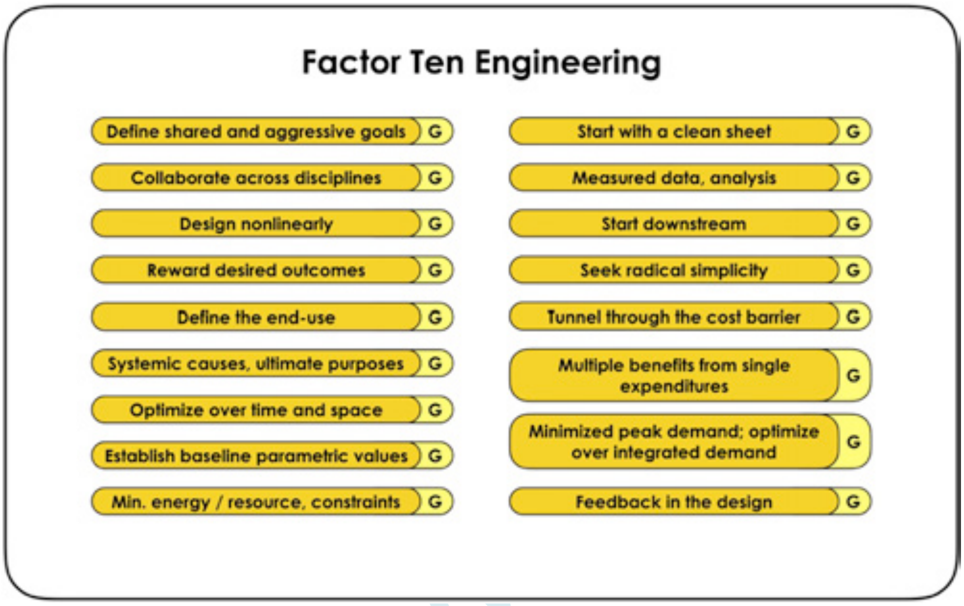


Figure A14. Activities of Factor Ten Engineering.

7 Appendix B: Mindsets in All Design Practices

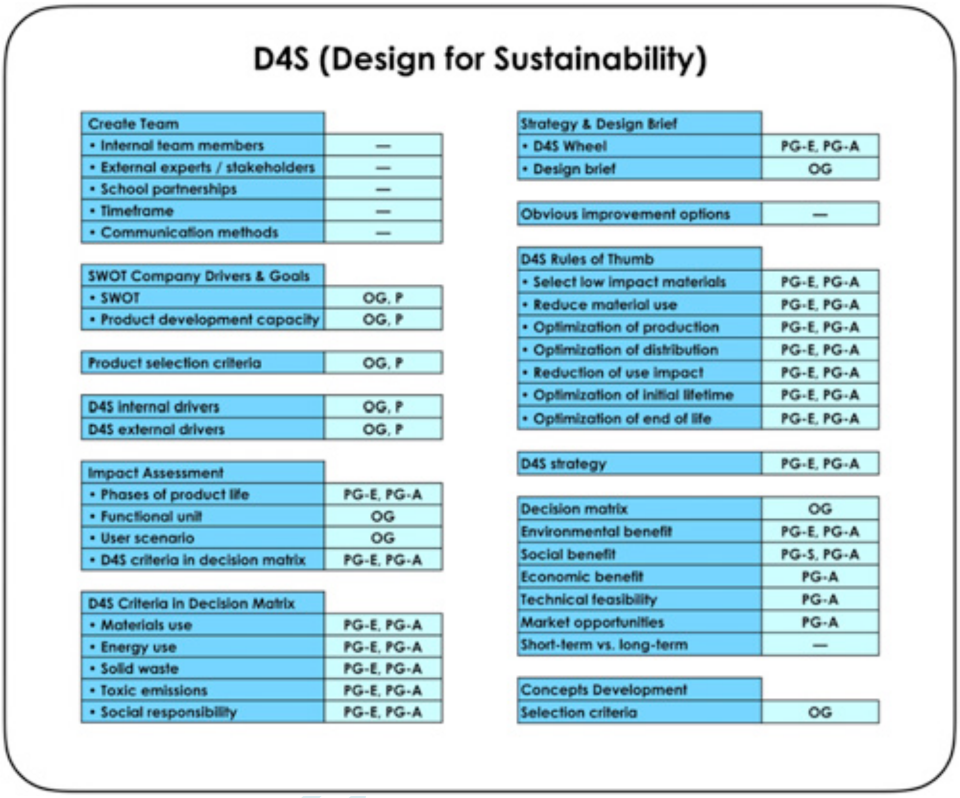


Figure B1. Mindsets of D4S.

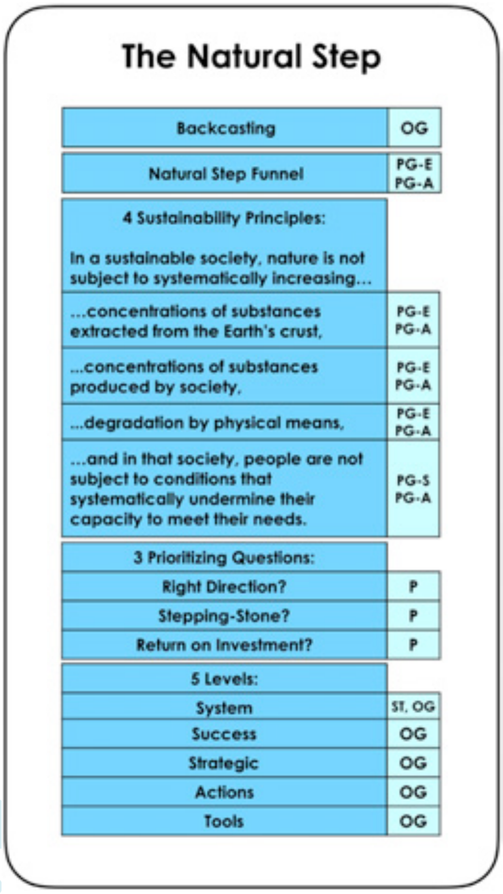


Figure B2. Mindsets of The Natural Step.

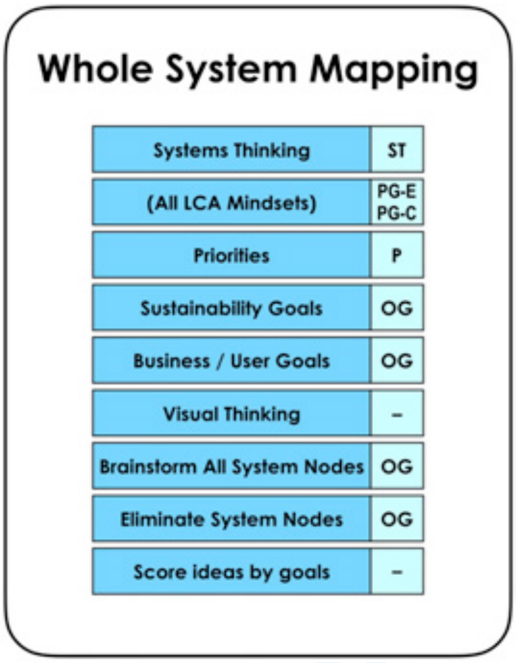


Figure B3. Mindsets of Whole System Mapping.

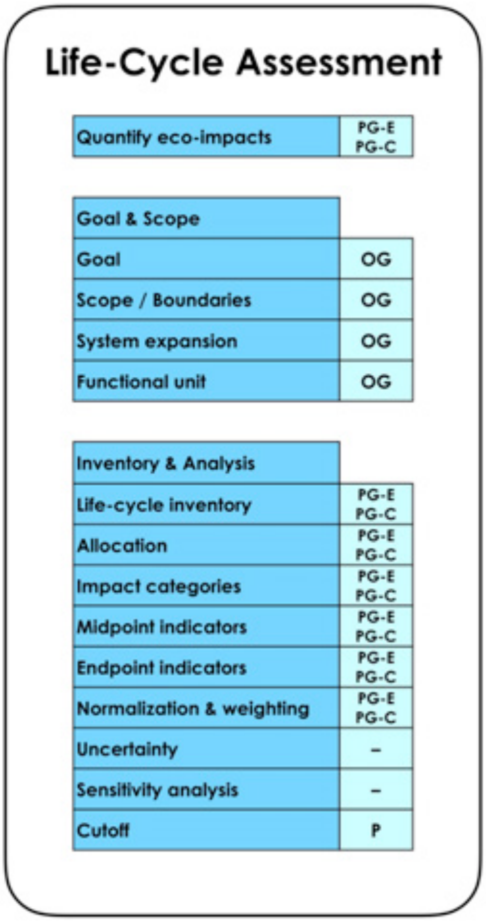


Figure B4. Mindsets of Life-Cycle Assessment.

Biomimicry

Nature as Model	OG
Nature as Mentor	-
Nature as Measure	OG

Nature's Principles:	
Life Creates Conditions Conducive To Life	PG-E, PG-A
Adapt to changing conditions:	PG-E, PG-A
• Incorporate Diversity	PG-E, PG-A
• Maintain Integrity Through Self-Renewal	PG-E, PG-A
• Embody Resilience Through Variation, Redundancy, Decentralization	PG-E, PG-A
Be Locally Attuned and Responsive:	PG-E, PG-A
• Leverage Cyclic Processes	PG-E, PG-A
• Use Readily Available Materials and Energy	PG-E, PG-A
• Use Feedback Loops	PG-E, PG-A
• Cultivate Cooperative Relationships	PG-E, PG-A
Use Life-Friendly Chemistry:	PG-E, PG-A
• Break Down Products into Benign Constituents	PG-E, PG-A
• Build Selectively with a Small Subset of Elements	PG-E, PG-A
• Do Chemistry in Water	PG-E, PG-C
Be Resource Efficient:	PG-E, PG-A
• Use Low Energy Processes	PG-E, PG-A
• Use Multi-Functional Design	PG-E, PG-A
• Recycle All Materials	PG-E, PG-C
• Fit Form to Function	PG-E, PG-A
Integrate Development With Growth:	PG-E, PG-A
• Self-Organize	PG-E, PG-A
• Build from the Bottom-Up	PG-E, PG-A
• Combine Modular and Nested Components	PG-E, PG-C
Evolve To Survive:	PG-E, PG-A
• Replicate Strategies that Work	PG-E, PG-A
• Integrate the Unexpected	PG-E, PG-A
• Reshuffle Information	PG-E, PG-A
Earth's Operating Conditions:	PG-E, PG-A
• Sunlight, Water, and Gravity	PG-E, PG-A
• Dynamic Non-Equilibrium	PG-E, PG-A
• Limits and Boundaries	PG-E, PG-A
• Cyclic Processes	PG-E, PG-A

Figure B5. Mindsets of Biomimicry (all 3 versions studied here share the same mindsets).

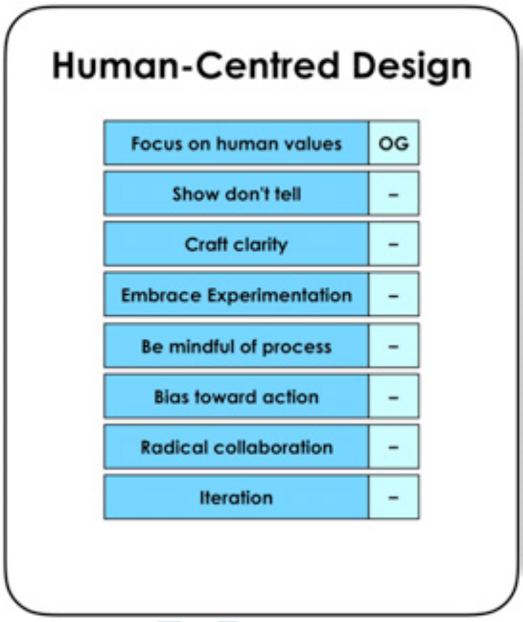
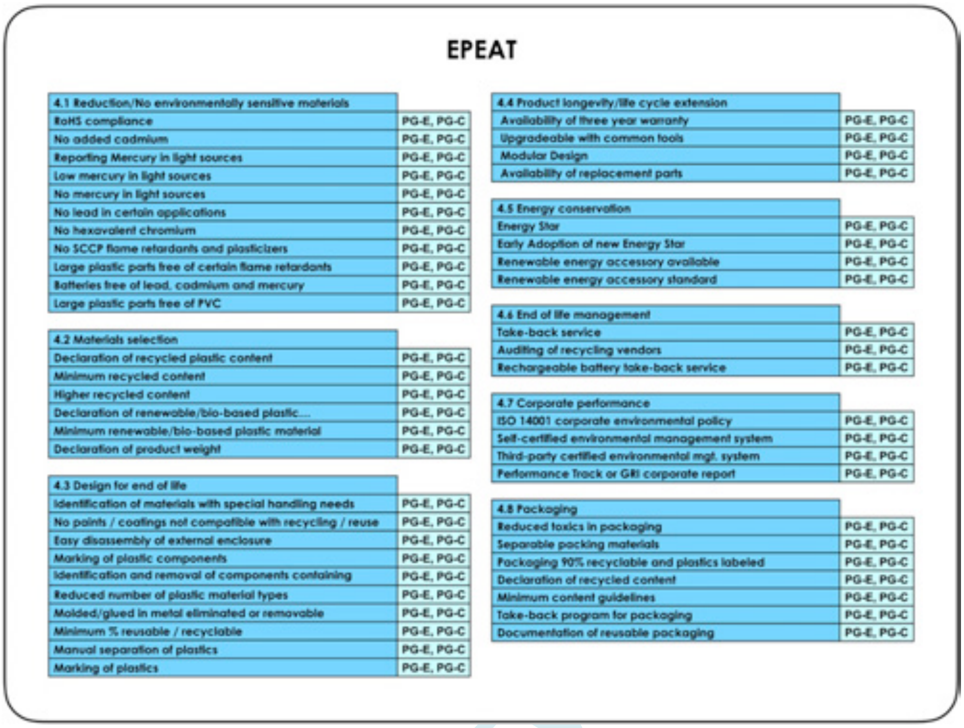


Figure B6. Mindsets of Human-Centred Design.



EPEAT

4.1 Reduction/No environmentally sensitive materials	
RoHS compliance	PG-E, PG-C
No added cadmium	PG-E, PG-C
Reporting Mercury in light sources	PG-E, PG-C
Low mercury in light sources	PG-E, PG-C
No mercury in light sources	PG-E, PG-C
No lead in certain applications	PG-E, PG-C
No hexavalent chromium	PG-E, PG-C
No SCCP flame retardants and plasticizers	PG-E, PG-C
Large plastic parts free of certain flame retardants	PG-E, PG-C
Batteries free of lead, cadmium and mercury	PG-E, PG-C
Large plastic parts free of PVC	PG-E, PG-C

4.2 Materials selection	
Declaration of recycled plastic content	PG-E, PG-C
Minimum recycled content	PG-E, PG-C
Higher recycled content	PG-E, PG-C
Declaration of renewable/bio-based plastic....	PG-E, PG-C
Minimum renewable/bio-based plastic material	PG-E, PG-C
Declaration of product weight	PG-E, PG-C

4.3 Design for end of life	
Identification of materials with special handling needs	PG-E, PG-C
No paints / coatings not compatible with recycling / reuse	PG-E, PG-C
Easy disassembly of external enclosure	PG-E, PG-C
Marking of plastic components	PG-E, PG-C
Identification and removal of components containing	PG-E, PG-C
Reduced number of plastic material types	PG-E, PG-C
Molded/glued in metal eliminated or removable	PG-E, PG-C
Minimum % reusable / recyclable	PG-E, PG-C
Manual separation of plastics	PG-E, PG-C
Marking of plastics	PG-E, PG-C

4.4 Product longevity/life cycle extension	
Availability of three year warranty	PG-E, PG-C
Upgradeable with common tools	PG-E, PG-C
Modular Design	PG-E, PG-C
Availability of replacement parts	PG-E, PG-C

4.5 Energy conservation	
Energy Star	PG-E, PG-C
Early Adoption of new Energy Star	PG-E, PG-C
Renewable energy accessory available	PG-E, PG-C
Renewable energy accessory standard	PG-E, PG-C

4.6 End of life management	
Take-back service	PG-E, PG-C
Auditing of recycling vendors	PG-E, PG-C
Rechargeable battery take-back service	PG-E, PG-C

4.7 Corporate performance	
ISO 14001 corporate environmental policy	PG-E, PG-C
Self-certified environmental management system	PG-E, PG-C
Third-party certified environmental mgt. system	PG-E, PG-C
Performance Track or GRI corporate report	PG-E, PG-C

4.8 Packaging	
Reduced toxics in packaging	PG-E, PG-C
Separable packing materials	PG-E, PG-C
Packaging 90% recyclable and plastics labeled	PG-E, PG-C
Declaration of recycled content	PG-E, PG-C
Minimum content guidelines	PG-E, PG-C
Take-back program for packaging	PG-E, PG-C
Documentation of reusable packaging	PG-E, PG-C

Figure B7. Mindsets of EPEAT Certification.

Cradle to Cradle Certification

1. Material Health	
Material ingredient identification	PG-E, PG-C
Technical nutrients	PG-E, PG-C
Biological nutrients	PG-E, PG-C
Banned List of substances	PG-E, PG-C
Toxicity assessment	PG-E, PG-C
Cradle to Cradle emission standards	PG-E, PG-C

2. Material Reutilization	
Material Reutilization Score	PG-E, PG-C
Nutrient management strategy	PG-E, PG-C
Take-back / recovery	PG-E, PG-C

3. Energy	
Quantify energy use & sources	PG-E, PG-C
% of renewable energy / carbon offset	PG-E, PG-C
Quantify embodied energy	PG-E, PG-C
Embodied energy / carbon strategy	PG-E, PG-C

4. Water	
Water stewardship strategy	PG-E, PG-C
Discharge permit	PG-E, PG-C
Water scarcity	PG-E, PG-C
Sensitive ecosystems	PG-E, PG-C
Water audit	PG-E, PG-C
Effluent assessment	PG-E, PG-C
Drinking water quality standards	PG-E, PG-C

5. Social Responsibility	
Human rights self-audit	PG-S, PG-C
Mgt. procedures for human rights	PG-S, PG-C
Full social responsibility self-audit	PG-S, PG-C
Positive social impact strategy	PG-S, PG-C
Material-specific audit	PG-S, PG-C
Issue-specific audit	PG-S, PG-C
Innovative social project	PG-S, PG-C
Third party social resp. assessment	PG-S, PG-C

Figure B8. Mindsets of Cradle to Cradle Certification.

Cradle to Cradle Book

Eco-effectiveness (doing good, not less bad)	PG-E PG-A ST
Waste equals food	PG-E PG-A
Technical nutrients	PG-E PG-C
Biological nutrients	PG-E PG-C
Respect Diversity	PG-E,S PG-A
Material health	PG-E PG-A
Inspiration from natural systems	ST

Figure B9. Mindsets of the Cradle to Cradle book.

Okala Practitioner

Product System Life Cycle	ST
Green marketing	PG-E, PG-A
Ecodesign in devel. process	ST, PG-E, PG-A
Stakeholder needs	---
Measuring env. performance	PG-E, PG-C
Okala impact factors	PG-E, PG-C
Using impact factors	OG, P

Process tree	ST, OG
Ecology for designers	PG-E, PG-A
Evolution of biosphere	PG-E, PG-A
Stressed biosphere	PG-E, PG-A
Challenging our beliefs	PG-E, PG-A
Achieving social equity	PG-S, PG-A

Ecodesign Strategy Wheel	
1. Innovation	
• Rethink how to provide the benefit	PG-E, PG-A
• Design flexibility for technological change	PG-E, PG-A
• Provide product as service	PG-E, PG-C
• Serve needs provided by associated	PG-E, PG-C
• Share among multiple users	PG-E, PG-C
• Mimic biological systems	PG-E, PG-C
• Use living organisms in product system	PG-E, PG-C
• Create opportunity for local supply chain	PG-E, PG-C
2. Reduced Material Impacts	
• No materials damage health	PG-E, PG-C
• No materials deplete natural resources	PG-E, PG-C
• Minimize quantity of material	PG-E, PG-C
• Use recycled or reclaimed materials	PG-E, PG-C
• Use renewable resources	PG-E, PG-C
• Use materials from reliable certifiers	PG-E, PG-C
• Use waste byproducts	PG-E, PG-C
3. Manufacturing Innovation	
• Minimize manufacturing waste	PG-E, PG-C
• Design for production quality control	PG-E, PG-C
• Minimize energy use in production	PG-E, PG-C
• Use carbon-neutral or renewable energy	PG-E, PG-C
• Minimize # of production steps	PG-E, PG-C
• Minimize # of components / materials	PG-E, PG-C
• Seek to eliminate toxic emissions	PG-E, PG-C
4. Reduced Distribution Impacts	
• Reduce product and packaging weight	PG-E, PG-C
• Reduce Product and packaging volume	PG-E, PG-C
• Develop reusable packaging systems	PG-E, PG-C
• Use lowest-impact transport system	PG-E, PG-C
• Source or use local materials...	PG-E, PG-C
5. Reduced Behavior and Use Impacts	
• Low-consumption user behavior	PG-E, PG-C
• Reduce energy consumption during use	PG-E, PG-C
• Reduce material consumption during use	PG-E, PG-C
• Reduce water consumption during use	PG-E, PG-C
• Eliminate toxic emissions during use	PG-E, PG-C
• Carbon-neutral or renewable energy	PG-E, PG-C
6. System Longevity	
• Design for durability	PG-E, PG-C
• Design for maintenance and easy repair	PG-E, PG-C
• Design for Reuse and exchange	PG-E, PG-C
• Create a timeless aesthetic	PG-E, PG-C
• Foster emotional connection to product	PG-E, PG-C
7. Transitional Systems	
• Design upgradeable products	PG-E, PG-C
• Design 2nd life with different function	PG-E, PG-C
• Design for reuse of components	PG-E, PG-C
8. Optimized End of Life	
• Integrate methods for used product	PG-E, PG-C
• Fast manual or automated disassembly	PG-E, PG-C
• Design recycling business model	PG-E, PG-C
• Use recyclable non-toxic materials	PG-E, PG-C
• Provide ability to biodegrade	PG-E, PG-C
• Design for safe disposal	PG-E, PG-C

Figure B10. Mindsets of Okala Practitioner.

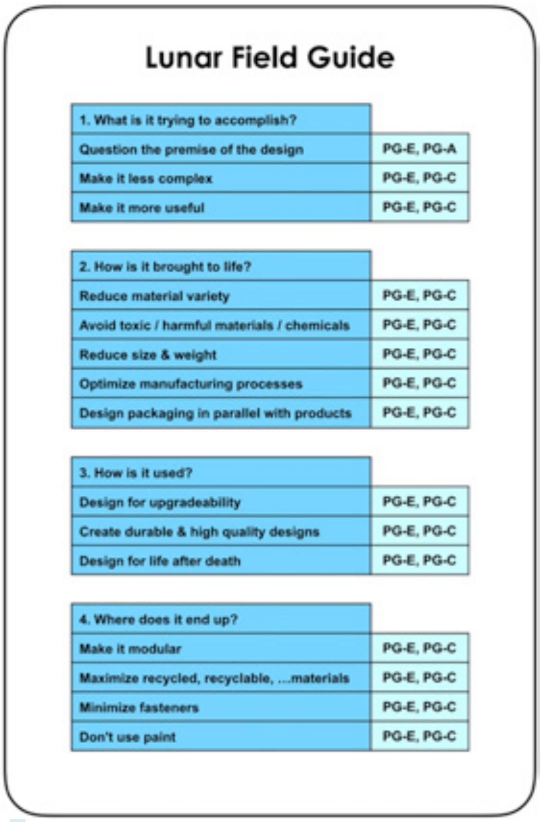


Figure B11. Mindsets of the Lunar Field Guide.

Living Principles

Systems Thinking	ST
Project Scorecard	C
Environment:	
• Behaviors	PG-E, PG-A
• Creation	PG-E, PG-A
• Durability	PG-E, PG-A
• Disassembly	PG-E, PG-A
• Supply Chain	PG-E, PG-A
• Waste	PG-E, PG-A
People:	
• Impacts	PG-S, PG-A
• Conflicts	PG-S, PG-A
• Desirability	PG-S, PG-A
• Need/Use	PG-S, PG-A
• Long View	PG-S, PG-A
Economy:	
• Systemic View	PG-S, PG-A
• Metrics	PG-S, PG-A
• Benefits	PG-S, PG-A
• Transparency & Truth	PG-S, PG-A
• Waste = Food	PG-E, PG-A
• Product > Service	PG-E, PG-A
Culture:	
• Visions	PG-S, PG-A
• Meanings & Reactions	PG-S, PG-A
• Systemic View	PG-S, PG-A
• Diversity	PG-S, PG-A

Figure B12. Mindsets of Living Principles.

12 Leverage Points

12. Constants, parameters, numbers	ST, OG, PG-A
11. Sizes of buffers and other stabilizing stocks, relative to their flows	ST, OG, PG-A
10. Structure of material stocks and flows	ST, OG, PG-A
9. Lengths of delays, relative to the rate of system change	ST, OG, PG-A
8. Strength of negative feedback loops…	ST, OG, PG-A
7. Gain around driving positive feedback loops	ST, OG, PG-A
6. Structure of information flows	ST, OG, PG-A
5. Rules of the system	ST, OG, PG-A
4. Power to add, change, evolve, or self-organize system structure	ST, OG, PG-A
3. Goals of the system	ST, OG, PG-A
2. Mindset or paradigm out of which the system arises	ST, OG, PG-A
1. Power to transcend paradigms	ST, OG, PG-A

Figure B13. Mindsets of 12 Leverage Points.

Factor Ten Engineering

10x improvement in efficiency	PG-E, PG-A
Checklist of mindsets	C
Ready	
• Shared goals	OG
• Collaborate across disciplines	---
• Nonlinear design	ST
• Rewards for desired outcomes	OG
Set	
• End-use	OG
• Causes / purposes	ST
• Optimize over time and space	PG-E, PG-A
• Baseline parametric values	PG-E, PG-A
• Theoretical minimum energy / resource use	PG-E, PG-A
• Constraints to… min. energy / resource use	PG-E, PG-A
Go	
• Start with a clean sheet	ST
• Measured data… not assumptions / rules	PG-A
• Start downstream	ST
• Radical simplicity	ST, PG-A
• Tunnel through the cost barrier	ST, PG-A
• Multiple benefits from single expenditures	ST, PG-A
• Peak demand	PG-E, PG-A
• Integrated / average demand	PG-E, PG-A
• Feedback	ST, PG-A

Figure B14. Mindsets of Factor Ten Engineering.