



WHAT GREEN DESIGN ACTIVITIES AND MINDSETS DRIVE INNOVATION AND SUSTAINABILITY IN STUDENT TEAMS?

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Abstract

What sustainable design practices can also drive innovation, and what practices do people value? Previous analysis of sustainable design methods, and the opportunism of designers generally, has suggested that design methods should actually be examined at the level of their component activities and mindsets, as each of these provides different advantages that designers could mix and match. This study performed workshops of three sustainable design methods for a total of 327 students, then surveyed students about which activities or mindsets within each design method drove innovation value, sustainability value, and any other value. The design methods tested were The Natural Step, Whole System Mapping, and Biomimicry. Qualitative and quantitative analyses of surveys found that some activities and mindsets were valued more than others for sustainability, innovation, or both, and to some extent revealed why. Some results were surprising and suggest new research directions.

Keywords: Sustainability, Innovation, Design methodology, Ecodesign, Design practice

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1 INTRODUCTION

Considering sustainability is often believed to inhibit design creativity (Collado-Ruiz and Ghorabi, 2010) but many have found it to improve product innovation (Aronson, 2013), (Keskin et al., 2013), (Charter and Clark, 2007). Previous sustainable design studies have lumped all sustainable design practices into a general unit (see previous citations), or compared design methods as units (Behrisch et al., 2011a) (Behrisch et al., 2011b), or studied new methods they proposed (Kobayashi, 2006), (Uang and Liu, 2013), (Ölundh, 2006). However, interviews with 17 industry practitioners found that designers generally use parts of a sustainable design method, or of multiple methods, but rarely follow any one method exclusively or strictly. This has been shown to be the case for traditional design practices as well (Visser, 1990). Designers use design methods as toolboxes, not tunnels, to find solutions.

Therefore, it is useful to deconstruct sustainable design methods into their components to see which components designers value, and why. Traditional design engineering methods have been deconstructed into components that were each measured for innovation value (Shah et al., 2003), (Hernandez et al., 2010), (Kramer et al., 2016). Some work has analysed general sustainable design practice to differentiate it from traditional design methods (Vallet et al., 2013). By contrast, this paper measures the innovation value and sustainability value of the components in three popular sustainable design methods.

Figure 1 shows how previous work (Faludi, 2016), (Faludi, n.d.) deconstructed the three sustainable design methods studied here into their component activities (what designers do: sketch, write, use post-its or software, etc.) and mindsets (what designers think about: ideas, frameworks, paradigms, etc.) Activities were categorized into Research (R), Analysis (A), Ideation (I), Building (B), Decision (D), Goal-setting (G), and Communication (C) types. Mindsets were categorized into Systems Thinking (ST), Checklists (C), Priorities (P), Determine Own Goals (OG), and Predetermined Goals (PG); the latter were subdivided into Environmental (PG-E), Social (PG-S), Abstract (PG-A), and Concrete (PG-C) goal types. Note that there are variants of Biomimicry, only one of which was taught here; also, some activities or mindsets of each method were not taught due to time constraints.

The Natural Step		Whole System Mapping		Biomimicry (as taught)	
Activities	Type	Activities	Type	Activities	Type
• Awareness / Vision	G, C	• Draw whole system map	A, C	• Define Problem Biologically	G
• Baseline	A	• Life-Cycle Assessment (LCA) [taught simplified]	A	• Discover Model Strategies Online	R
• Creative Solutions	I	• Prioritized design spec	G	• Discover Models in Life	R
• Decide on Priorities	D	• Brainstorm on System Map	I	• Learn Life Model Strategies	A
Mindsets	Type	• Estimated LCAs [not taught]	A	• Translate to Buildable Things	I
• Backcasting	OG	• Decide	D	• Choose Nature's Principles	G
• Natural Step Funnel	PG-E-A	Mindsets	Type	• Brainstorm Nature's Principles [not taught]	I
• 4 System Conditions [4 mindsets]	PG-E/S/A	• Whole-Systems Thinking	ST	Mindsets	Type
• 3 Prioritizing Questions [3 mindsets]	P	• Life-Cycle Assessment	PG-E-C	• Nature as Model	OG
• 5 Levels [not taught]	ST, OG	• Priorities	P	• Nature as Measure	—
		• Sustainability Goals	OG	• Nature as Mentor	OG
		• Business / User Goals	OG	• Nature's Principles	PG-E/A/C
		• Visual Thinking	—		
		• Brainstorm All System Nodes	OG		
		• Brainstorm to Eliminate Steps	OG		
		• Score Ideas by Goals	—		

Figure 1. Activities and mindsets in the design methods studied, and their categorizations.

To summarize Figure 1's design methods for those unfamiliar with them: The Natural Step uses the idea of "Backcasting" to start with the goal (Awareness / Vision) of perfect sustainability (as defined by the Four System Conditions), perform a gap analysis between it and the present situation (Baseline), ideate new possibilities (Creative Solutions), and choose what to act on (Decide on Priorities), using Three Prioritizing Questions. Whole System Mapping visually maps the product's system (Draw Whole System Map), then uses Life-Cycle Assessment (LCA) to find environmental hot-spots, which inform the Prioritized Design Spec; then Brainstorm on System Map ideates solutions, using the system map to ensure ideas for everything in the system (Brainstorm All System Nodes) and to push more radical ideas (Brainstorm to Eliminate Steps); winning ideas are chosen by comparing to the design spec (Decide). Biomimicry (as taught) redefines the design problem to be solved (Define Problem Biologically), then

inspiration is sought in nature (Nature as Model, Nature as Mentor), first through physical objects (Discover Models in Life, Learn Life Model Strategies) then online via AskNature.org (Discover Model Strategies Online); these ideas are then Translated to Buildable Things; resulting solutions can be tested for compatibility with nature (Nature as Measure, Nature's Principles), and Nature's Principles are also used for ideation.

Previous work hypothesized that different categories of activities and mindsets provide different benefits, hence the tendency for design methods to balance several categories. This paper tests the hypothesis that Research and Ideation activities primarily drive innovation, while Goal-Setting and Analysis activities drive sustainability. Participants in workshops of the three methods were surveyed for their opinions of what drove innovation and sustainability.

However, the mere existence of an activity or mindset does not mean it is useful for sustainability, innovation, or any other benefit. In order to recommend more effective design practices, this study also surveyed participants about what activities and mindsets they valued or did not, for both innovation and sustainability, and why. The resulting data may allow practitioners to use only the best tool(s) for the job at hand, or mix and match components of design methods.

In the following sections, Methods presents what data was gathered and how it was analysed. Results presents quantitative and qualitative analyses of what students valued and criticized, what they related to sustainability and innovation, and why, as well as validation by comparing to final reports. The Conclusion summarizes key findings and implications.

2 METHODS

This study mixed quantitative and qualitative methods to assess what students valued and why, following Creswell's "concurrent nested" approach (Creswell, 2013). The overall research plan follows Blessing and Chakrabarti's design research method #4 (Blessing and Chakrabarti, 2009), with this paper describing the "descriptive study II" phase.

Workshops on each design method were given for students in UC Berkeley's undergraduate class ME110 "Introduction to Product Development" and graduate class ME290P "Managing New Product Development". To check validity and repeatability, each workshop was performed for two classes; classes varied in size, demographics, and instructors, but had similar curriculum teaching Human-Centred Design. Workshops occurred at roughly the same class week for 5 of 6 workshops: after multiple concept development and early prototyping, but before final concept selection. When two workshops were given to the same class, they were given in the same week to avoid differences in stage of design process. In all classes, students worked in teams of 3 – 6 on semester-long projects, either industry-sponsored or their own. Table 1 lists classes and workshops in the order given and the number of survey responses for each, with the percentage of the class that responded. The teaching assistant in ME110 2015 was this paper's lead author, and all courses were taught by one of the co-authors, except ME110 Summer 2016, which was taught by an external lecturer. Over half the students in all courses were mechanical engineering students, with a mix of other majors that included other fields of engineering, computer science and business; 68% were male, 32% female.

Table 1. Classes, dates, and number of survey responses for all workshops.

Class	Workshop #1	Surveys	Workshop #2	Surveys
ME110 2015 Spring (week 12 of 16)	The Natural Step	71 (84%)	Whole System Mapping	65 (78%)
ME290P 2015 Fall (week 13 of 16)	The Natural Step	18 (51%)	—	—
ME110 2016 Spring (week 12 of 16)	Whole System Mapping	69 (73%)	Biomimicry	66 (70%)
ME110 2016 Summer (week 5 of 10)	Biomimicry	38 (76%)	—	—

After each workshop, students were surveyed on their reactions to that design method, including the questions:

- In your opinion, what activities or mindsets from the design method were most useful? (If none, say none.)

- In your opinion, what activities or mindsets were not valuable, or not valuable enough to be worth your time? (If none, say none.)
- In your opinion, which of the design method's activities or mindsets gave you innovative ideas? (If none, say none.)
- In your opinion, which of the design method's activities or mindsets improved product sustainability? (If none, say none.)
- In your opinion, did anything in the design method provide any other value, not related to innovation or sustainability? If so, when or how?

Students were not told what they should consider activities or mindsets, as in Figure 1, but were free to write anything they identified in the workshop. This caused intriguing insights, as the Results section will describe. All survey text was qualitatively coded for specific activity / mindset mentioned, sustainability, innovation, other benefit, valued or criticized, and reasons why. Initial "open coding" of activities / mindsets and reasons for benefit or criticism were clustered into code categories for final coding. MaxQDA software was used to quantify co-occurrences of these codes in text. For example, the survey text *"The visioning process was the most useful aspect of this workshop. By picturing what the ideal conditions could look like for our product, this expanded our view of the ways that it could be designed, implemented, and used"* was tagged with four codes: "Awareness / Vision activity", "valued", "reason – envisioning perfection", and "reason – broaden scope". The text *"System mapping was the best way of visualizing and identifying the effect a product would have on the environment"* was coded "Drawing System Map activity", "sustainability-related", "valued", "reason – visual", and "reason - focus / clarify thought". Most codes for activities / mindsets matched those identified in previous research (Figure 1), but not all. Such code co-occurrences were counted only once per student, to avoid vocal minorities or percentages of respondents exceeding 100%. Occurrences counted even outside of the specific survey question if the text related to that question. The lead author coded 30 surveys to determine coding rubrics and training for the research assistant, then the rest of the 327 surveys were coded by both the primary investigator and a research assistant, with intercoder reliability Cohen's Kappa of .82 with no revision of coding needed.

To strengthen findings, student team final reports were also coded by this rubric, to check validity by triangulating against surveys. Final reports provided longer-term data (three to five weeks later) and, unlike the surveys, had no requirements for students to mention the workshops at all. These reports do not prove survey results true or false, but illuminate which activities / mindsets students value enough to mention unprompted, and value both immediately after the workshop and at the end of the project. Such activities / mindsets are likely to be more valuable overall.

3 RESULTS

3.1 What Students Valued and Criticized, And Why

The following graphs count how many respondents valued or criticized activities or mindsets in their survey text; the graphs do not count the strength of praise or criticism in each response. Fewer than half of respondents listed reasons *why* they valued activities or mindsets, with no one reason occurring over 9% and most only mentioned by one or two students, so all reasons were analysed qualitatively.

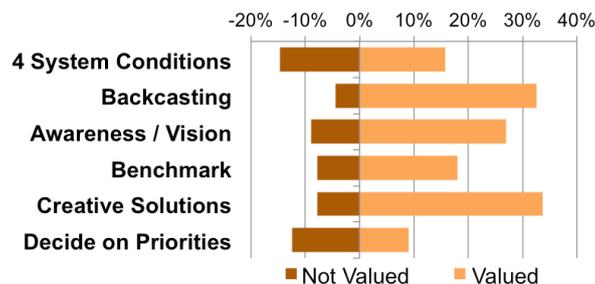


Figure 2. The Natural Step: Percent of respondents mentioning activities / mindsets as valued or not. N = 89.

For the Natural Step, Figure 2 shows that the Backcasting mindset and the Creative Solutions activity were most often valued; The Four System Conditions mindset was criticized almost as much as valued,

and the Decide on Priorities activity was criticized more than valued. Students mentioned the System Conditions as a set, almost never individually. No students mentioned the Three Prioritizing Questions mindset in the Decide on Priorities activity.

Backcasting was valued for envisioning perfection (for example, *"This method of design allowed for our team to visualize an idealized design for our product, and determine what a few solutions were that could make that ideal possible, and feasible. This was advantageous, as it allowed for us to aim high for the sustainability of the product."*) Some mentioned this as a business strategy benefit (*"It is useful to think about where we are now versus where we want to be. Whether this is from the perspective of trying to design for sustainability or not, it is always important to think about how to achieve your goal."*) It was also valued as a new lens and for broadening scope (*"It helped us consider a different way of thinking about the products we wanted to sell and how it affects the community rather than the narrow view of our specific customer base."*) As Backcasting encompasses all four activities, this may be considered praise for them all.

The Creative Solutions activity was mostly valued for innovation (*"Concepts/Brainstorming: Got our creative juices flowing by thinking of new ways to reach our goal."* and *"I think the most useful part of this workshop was the concepts row in which we were able to brainstorm a ton of ideas, even if some seemed ridiculous, and broaden our perspective to lead to more innovation."*) Some of the value may be due to designers enjoying any ideation activity (*"I always like brainstorming..."* and *"Brainstorming as usual was the most useful."*)

The Four System Conditions mindset received nearly as much criticism as praise; 9% of students wrote that the mindset was difficult to understand. It was generally valued for envisioning perfection, as Backcasting was. The Decide on Priorities activity was criticized largely for being unactionable (*"we have no decision making power here"* and *"It was hard to connect some points to our specific goals because our business model relies heavily on what other companies are already doing"*); other criticisms related to the time in the design process or the value of the Creative Solutions activity (*"deciding was probably the least useful, as significant parts of our design were thought through, and that some of the steps seemed to cover too wide of a scope to create useful concepts to decide on."*) Overall, The Natural Step received roughly twice as much criticism for unactionability than the other two design methods.

Other activities and mindsets were mostly valued for focusing / clarifying thought, envisioning perfection (especially the Awareness activity), and providing a new lens. Other benefits included convergent thinking, broadening scope, and enjoyment. All activities and mindsets were criticized for unactionability; most only by one to three students, but Awareness was called unactionable by eleven.

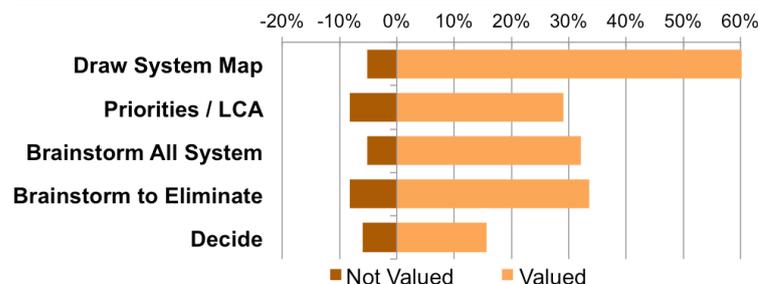


Figure 3. Whole System Mapping: Percent of respondents mentioning activities / mindsets as valued or not. N = 134.

For Whole System Mapping, Figure 3 shows that the activity Draw System Map was valued strikingly often—far more than any other activity or mindset in any method studied here. Students valued it for several reasons: 7-8% of respondents valued it for being visual and/or for focusing / clarifying thought (*"Much more focused and tangible than the Natural Step method"*, or *"we can really pinpoint the problem areas in the design process by laying them all out on paper first."*) Several others valued it for broadening scope (*"It was good to see the whole life cycle of our product because it forces us to step back and look at the bigger picture. Allow us to see some of the problems we haven't seen before"*).

Brainstorming was also highly valued; surprisingly, students mentioned the Brainstorm activity as two different activities, based on the two mindsets "Brainstorm All System Nodes" and "Brainstorm to Eliminate Steps", (listed in graphs as "Brainstorm All System" and "Brainstorm to Eliminate"), though they happened simultaneously. This shows the importance of interplay between mindsets and activities. It also showed students valued it for the specific activity, not merely as a generic ideation activity.

Brainstorm All System Nodes was slightly more valued for being visual or broadening scope, while Brainstorm to Eliminate Steps was more valued for being a new lens ("I really liked it, especially the skipping steps part, because it made me think in a different way") or for focusing / clarifying thought ("Eliminating System Nodes really helped force our group to see what we don't need in our overly complicated water bottle.")

Priorities / LCA was also highly valued, mostly for focusing / clarifying thought ("It also helped figure out where the biggest impact on the environment would be in the life of a product. It helped us conceptualize what is actually going on!") Every activity was valued for being visual and for providing a structured process. No more than one or two students mentioned disliking specific activities / mindsets for specific reasons. Four students criticized Drawing System Map, Brainstorming on System Map, or Brainstorming Eliminating Steps as being unactionable.

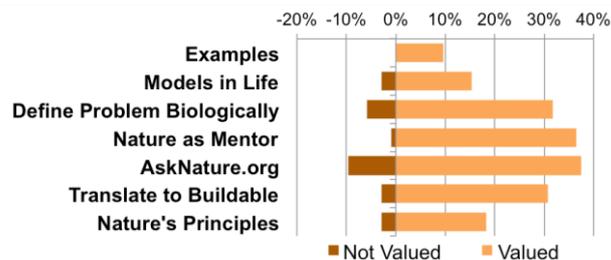


Figure 4. Biomimicry: Percent of respondents mentioning activities / mindsets as valued or not. N = 104.

For Biomimicry, Figure 4 shows that the Nature as Mentor mindset and the Discover Model Strategies Online activity (simply called "AskNature.org" by most students, and thus hereafter) were most highly valued, though AskNature.org was also most criticized. The summer class complained of slowness, possibly due to internet problems that day. Define Problem Biologically and Translate Into Buildable Things were also highly valued.

Data on why students valued Biomimicry was sparse. However, sixteen benefits were mentioned. The Nature as Mentor mindset, Discover Models in Life (simply "Models in Life" in the graph), and AskNature.org activity were mentioned as providing a new lens ("AskNature ...provided value in reminding us that there are numerous available resources outside of where we've been looking.") Nature as Mentor, Asknature.org, and Nature's Principles were mentioned as being interesting / engaging ("the AskNature segment taught me some of the fascinating designs that nature has to offer.") Only eight criticisms were mentioned; five called Discover Models in Life, Define Problem Biologically, Asknature.org, or Translate into Buildable Things unactionable.

Several students in both classes listed the mere mention of biomimicry example products during the introductory lecture as valuable ("I loved hearing about how biomimicry had been used in other products and services, it was inspiring.") This was unexpected, as examples are not activities or mindsets from the design method itself, but we believe they reinforce the Nature as Mentor mindset.

3.2 Driving Innovation and Sustainability

Rates of valuing activities or mindsets differed from reported rates of them driving sustainability and/or innovation. Some were valued for one or the other, some for both, some for other benefits, and some without mention of why. The following graphs count mentions of sustainability and innovation. As above, they do not count enthusiasm of responses, only number of respondents.

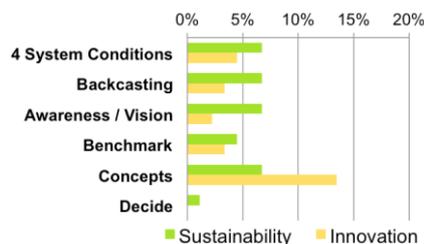


Figure 5. The Natural Step: Percent of respondents mentioning activities / mindsets driving sustainability or innovation. N = 89.

For The Natural Step, Figure 5 shows that students most often mentioned the Creative Solutions activity driving innovation. This was expected, since it is the only ideation activity. Surprisingly, Creative Solutions also scored as well or better in driving sustainability as anything else in the design method, despite Four System Conditions, Awareness / Vision, and Benchmark all existing solely to define sustainability, with Four System Conditions the theoretical heart of the method. Some quotes imply it may be because ideation with a sustainability focus feels more productive than analysis (*"Brainstorming was the most useful part, it made us think about ways this could apply to our project right now"*). Since no more than 7% of respondents mentioned any activity or mindset in the context of sustainability (despite the method as a whole being mentioned most often for sustainability), the ubiquity of these ideas is unclear. As mentioned earlier, the Decide on Priorities activity was criticized more than valued. Overall, most activities and mindsets were mentioned more for sustainability than innovation.

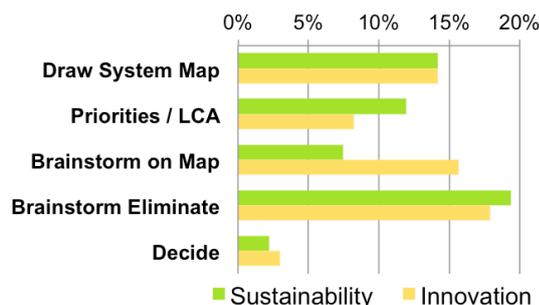


Figure 6. Whole System Mapping: Percent of respondents mentioning activities / mindsets driving sustainability or innovation. N = 134.

For Whole System Mapping, Figure 6 shows that Draw System Map, while highly rated, was not remarkably high as it was for general value in Figure 3; this may be because so many respondents valued it for focusing thought and broadening scope, which can be business benefits. The Brainstorm activity / mindsets were, as expected, most mentioned for driving innovation; surprisingly, Brainstorm to Eliminate Steps was rated highest for sustainability, rather than Priorities / LCA, whose entire purpose is to set sustainability priorities. As noted above, it may be because ideation feels more productive (*"Thinking of where exactly we can focus our attention to and eliminate some steps led to us thinking of how we can best acquire / reuse materials / products."*) Decide rated low. Overall, most activities and mindsets were mentioned at similar levels for sustainability and innovation.

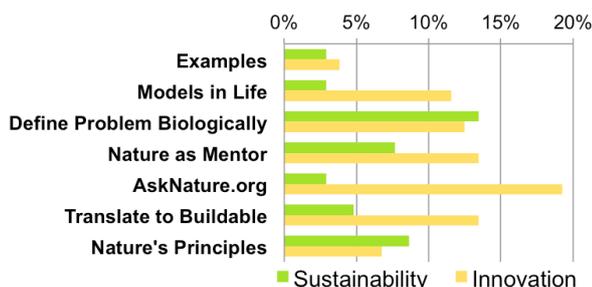


Figure 7. Biomimicry: Percent of respondents mentioning activities / mindsets driving sustainability or innovation. N = 104.

For Biomimicry, Figure 7 shows that the AskNature.org activity was most valued for innovation, but little mentioned for sustainability—they viewed it as problem-solving (*"AskNature becomes akin to a search engine for my bio-inspired ideas."*) Surprisingly, innovation value was not entirely in research or ideation (Discover Models in Life, Asknature.org, Translate into Buildable Things), but also ascribed to goal-setting activities (Define Problem Biologically and Nature's Principles). This may be because they offered a new lens (*"learning how to frame the problem in the ways of nature leading to new ideas or ways of solving our issues."*) Define Problem Biologically was reported most valuable for sustainability, not Nature's Principles, as expected. Overall, most activities and mindsets were mentioned much more for innovation than sustainability.

3.3 Comparing To Final Reports

Surveys were compared against final reports to check validity. Reports or presentations in all classes except ME110 Summer 2016 required a Design for the Environment section, but without criteria for this study. Thus, many contained no mentions, or vague mentions to entire design methods.

For The Natural Step, five of seven inclusions were photographs of workshop results without comment, not allowing differentiation by activity. Only two contained descriptive text; both described goals from Awareness / Vision, and one mentioned Backcasting. All mentions were sustainability-related. Small sample size makes these results inconclusive.

For Whole System Mapping, nine of 27 reports mentioned or had photographs of Draw System Map and Priorities / LCA activities (however, two LCA references were mislabelled system maps). Both were mentioned as focusing / clarifying thought. Decide, Brainstorm on Map, and Brainstorm to Eliminate Steps only appeared in four, five, and six reports respectively. This reinforces the value of the Draw System Map activity. Perhaps ideation benefits are shorter-lived than analysis or goal-setting when more ideation happens throughout the project; this is speculation. All mentions were sustainability-related, but one mention of Brainstorm to Eliminate Steps was also innovation-related. Biomimicry was seldom mentioned in reports, with zero in any ME110 2016 summer reports, perhaps because that instructor did not require a "design for environment" section; but even in 2016 spring, it appeared half as often as Whole System Mapping. All activities and mindsets appeared one to three times, except Examples and Nature's Principles (not mentioned). All were listed in sustainability contexts, but all three text mentions also related to innovation, perhaps reinforcing the survey results primarily valuing Biomimicry activities / mindsets for innovation.

3.4 Limitations

These results should not be assumed generalizable, because values / criticisms differ by context; even here they sometimes varied greatly by class and other factors. Analyses of this data are underway to compare by demographics. Student studies should be validated by industry studies (Cash et al., 2013), (Gonçalves et al., 2014). Future research may also test surveys against third parties rating the sustainability and innovation of design outcomes, to validate participants' self-perceptions. Finally, future studies should examine whether highly-valued activities or mindsets can be effectively used outside of their design method, or if they require accompanying lower-value activities / mindsets.

4 CONCLUSION

Different design activities and mindsets are valued differently, as hypothesized. Overall, Research and Ideation activities were valued more for innovation, Goal-setting and Analysis activities were valued more for sustainability; however, the difference was smaller than expected, and Ideation activities were valued as highly for sustainability as Goal-Setting or Analysis. Popularity of ideation activities for not just innovation but also sustainability may explain why so many companies believe that thinking about sustainability while brainstorming is all that is needed for sustainable design.

Some activities and mindsets stood out. The Draw System Map activity from Whole System Mapping was by far the most often valued from any design method, even beyond its reported value for innovation or sustainability; many valued it for focusing thought and broadening scope. The two activities most often mentioned for innovation were Biomimicry's AskNature.org and Whole System Mapping's Brainstorm to Eliminate Steps; the latter was also the most mentioned for driving sustainability. The Natural Step's Four System Conditions mindset was most often criticized, with students calling it hard to understand. The primary criticism for all activities / mindsets of all design methods was being unactionable; this is a common industry criticism of all sustainability practices.

Free-text surveys provided insight on the previous research's taxonomies of activities and mindsets. In Whole System Mapping, students surprisingly distinguished one activity as two, based on the two mindsets used simultaneously during the activity (Brainstorm All System Nodes and Brainstorm to Eliminate Steps). This suggests other design activities might be strengthened by hybridizing them with new mindsets. In Biomimicry, students listed lecture examples as valuable, despite them not being identified by researchers as a mindset or activity. This could guide teachers of Biomimicry.

We hope this analysis of what students value in sustainable design methods, and why, can enable improved design practice, just as user testing enables improved product designs. To spread adoption,

design methods should not only be valued for sustainability, but also business benefits such as innovation and others listed above. This could make sustainable design simply good design practice.

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