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# Do Student Trials Predict What Professionals Value in Sustainable Design Practices?

*When teaching sustainable design in industry or academia, we should teach design methods, activities, and mindsets that are most effective at driving real change in a industry. However, most studies of design practices are performed on students, not on professionals. How strongly do student perceptions of value predict those of industry teams designing real products? This study provided workshops on three sustainable design methods (The Natural Step, Whole System Mapping, and Biomimicry) for 172 professionals and 204 students, applying the methods to their actual products being developed. It surveyed both populations about which activities or mindsets within each design method provided sustainability value, innovation value, and overall value. Quantitatively, student results did not strongly predict professional opinions; professionals chose clearer favorites and valued more things. However, qualitatively, student results did predict the reasons why professionals would value the design activities and mindsets. Therefore, care should be taken to choose appropriate participants for the questions being asked in sustainable design research.*
[DOI: 10.1115/1.4043200]

*Keywords: sustainable design, design for environment, design methods, design methodology, design process, design education, product design*

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## 1 Introduction

Designers and engineers build our material world, so they hold great power and responsibility to make our world more sustainable. Professionals build today's world, and students will build tomorrow's. How can we maximize the effectiveness of their sustainable design practices? Empirical studies testing the effectiveness of sustainable design practices are needed, as others have argued. Deutz et al. said, "Formulating such an innovative approach requires first understanding current practices of eco-design in industry" [1]. Lofthouse argued, "Designers do not have the right mechanisms to support the integration of eco-design into early product development. Research has suggested that many tools fail because they do not focus on design, but are aimed at strategic management or retrospective analysis" [2].

Students are often used to test design methods [3–6]. Sometimes students are tested because the studies are meant to improve education [7,8]; such studies are important to train the next generation of engineers and designers in sustainability [9]. However, most often, students are used merely because they are a convenient population to test, and results are hoped to be universal. This may be problematic, as students may not represent professionals, having less strategic approaches, and less attention to detail [10] as well as lacking subject matter expertise and other experience-based wisdom. Thus, it is important to test how well results in universities match results in the professional world. While very few studies do so, those that do are valuable. Some have shown commonalities [11]; others have shown differences in preferred inspiration sources [12] as well as deeper thought processes [13]. Even without more years of experience, engineers with professional experience operate differently than those with university-only experience [14]. However, tightly defined tasks can produce similar results in both novices and experienced professors [15]. Knowledge of these commonalities and differences can help transfer best practices from academia to industry [16] and may even aid teaching practices.

Contributed by the Design Education Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received July 18, 2018; final manuscript received February 27, 2019; published online May 13, 2019. Assoc. Editor: Scarlett Miller.

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In this study, undergraduate students (engineering and business majors) and professionals (including designers, engineers, and managers) were compared by what activities and mindsets they found valuable for real product development within three sustainable design methods. The students were in project-based product design classes using Human-Centered Design to go from initial needs to detailed design and prototyping, applying the design methods to their projects (some self-initiated, some for industry). The professionals applied the design methods to their actual products in development. While workshops are still somewhat artificial, these conditions provided far more realistic context than more controlled and specified tests. The goal was to inform how sustainable design methods might be combined or streamlined in real-world contexts. Sustainable design is complex—a "wicked" problem [17]—and as such, it benefits more from combining diverse approaches than from even the best single approach [18]. However, time and money limitations restrict how many sustainable design practices can be integrated into a design team's process. Santolaria et al. found that "the integration of environmental criteria into strategic plans" was most hampered by "lack of tangible benefits," but "more than 90% of respondents believe that innovation could be a future catalyst for the integration of eco-design in companies" [19]. Therefore, research is required to discover the tangible benefits of different sustainable design practices. The goal of this paper is to determine whether testing sustainable design methods with students can provide adequate insight into what professionals will value.

In addition to sustainability being complex, design practice is also complex, due to the extreme variability of personal practices and the tradeoffs between innovation, quality, cost, and other factors. Even in the same overall design method, different design activities can cause different user feedback on design outcomes [20]. Even when a design method is highly valued, practitioners do not slavishly follow it, but opportunistically perform more or less of some activities for one project than others [21]. As Homans described it, "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" [22]. Thus, this study's primary basis of comparison was not the design methods overall, but the components comprising them.

The three green design methods tested here were The Natural Step [23,24], Whole System Mapping [25,26], and one of several variants of Biomimicry [27–31], all taught as shown in Fig. 1. However, as mentioned above, these design methods were not the primary unit of analysis, but rather, their constituent components. These components were "activities" (something physically performed, such as writing, calculation, or CAD modeling) and "mindsets" (something conceptual, such as mental models, ideas, or entire paradigms). Other research has described these more fully [32]. Figure 1 breaks down all three green design methods into these components. Activities were classified as Research [R], Analysis [A], Ideation [I], Building [B], Decision [D], Goal-setting [G], and Communication [C] types. Mindsets were classified as Systems Thinking [ST], Checklists [C], Priorities [P], Determine Own Goals [OG], and Predetermined Goals [PG]; the latter included Environmental [PG-E], Social [PG-S], Abstract [PG-A], and Concrete [PG-C] goals.

Previous work described student results [33] and professional results [34] recommending the most valuable activities and mindsets to practitioners, as well as suggesting possibilities for mixing and matching components from different design methods. This study focuses only on the similarities and differences of the two populations, hypothesizing that undergraduate and graduate engineering and business students could serve as a proxy for professional designers, engineers, and managers. Specifically, the hypotheses were that, within all three design methods, both populations would agree on:

- Which components provided the most and least overall value
- Which components provided the most and least sustainability value
- Which components provided the most and least innovation value

## 2 Methods

This section describes the methods for recruiting participants, participant demographics, data collection, and analysis procedures. The three design methods were taught by this paper's lead author in separate workshops on separate dates. Student participants were in UC Berkeley's undergraduate class ME110 "Introduction to Product Development" and graduate class ME290P "Managing New Product Development: Design Theory and Methods"; both are electives where the instructor built the workshops into the class schedule, so all students participated. Their workshop participation was not graded, but they were graded on whether or not they responded to the surveys. As mentioned above, these classes went from initial needs to detailed design and prototyping, either for industry sponsors or their own projects. Professionals were recruited by various means: o2 network for sustainable design email lists, the Stanford product design alumni email list, the UC Berkeley mechanical engineering graduate student email list, the lead author's professional connections, the Greenermind Summit 2016 in Mendocino, CA, and the SustsinableBrands 2016 conference in San Diego, CA; in addition, some participants "snowballed" recruitment by recommending others. As mentioned above, professionals applied the design methods to their actual products in development; this occurred at various stages of the design process depending on workshop timing.

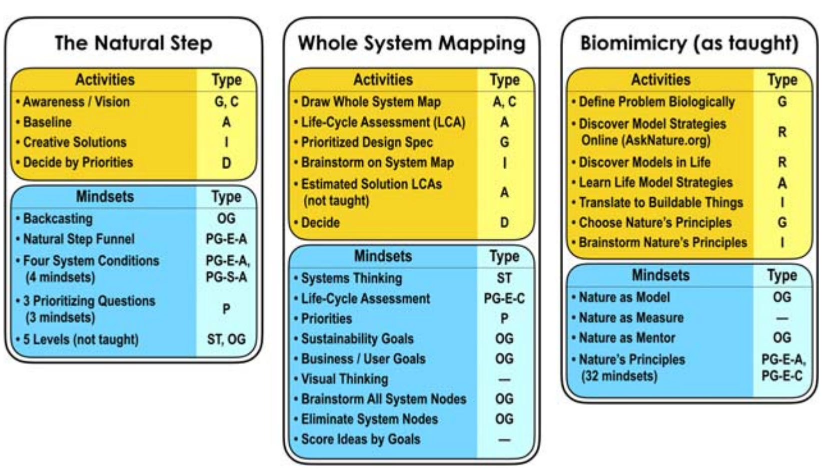


**Fig. 1 Activities and mindsets comprising the studied design methods, with categorizations**



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### 2.1 Participant Demographics.

**2.1 Participant Demographics.** In total, 29 workshops were performed for 520 participants; 258 were professionals from over 30 different companies, 262 were undergraduate and graduate students. Students who worked outside school were still considered students, not professionals. Workshop sizes ranged from 3 to 50 participants in professional workshops and 35–94 for student workshops. Because the purpose of this study was to examine product design teams, 26 professionals were disqualified for holding nonrelevant jobs (marketing, student intern) or working in nonrelevant industries (architecture); after this, there were 232 qualified professional participants. In addition, 60 professionals and 58 students did not respond to surveys, leaving 172 qualified professional and 204 student respondents. In order to increase the reliability and generalizability of results, each design method was workshopped with multiple teams on different occasions. For professionals, each workshop was performed for five or more companies; for students, each was performed for two classes. Companies included product manufacturers (52% of respondents) and product development consultancies (34% of responses, with 14% of responses leaving company type blank); small firms (from under ten up to 100 employees) and large firms (from 100 to over 10,000 employees). Industries for both professional and student teams included consumer electronics, apparel, furniture, housewares, medical devices, and others. Most participants received two or more workshops.

To minimize "carryover effect," order effects, and interaction bias, these workshops were performed in different orders for different companies and student classes and were usually performed several weeks or months apart. However, due to logistical limitations, all students receiving two workshops received them 2 days apart, and four company workshops for one company were performed the same day or consecutive days. Most student workshops occurred in the same stage of the design process: week 12 or 13 of a 16-week class (after "multiple concept development" and "early prototyping" was taught, but before "final concept selection"); however, one class received its workshop in week 5 of a 10-week class (after "multiple concept development" but before "early prototyping"). Professional workshops occurred at various stages during the design cycle. While sustainability is always best considered early in the design process, this could not be controlled due to the logistics of classes and company participants.

Table 1 shows the demographics of professionals and students, with numbers and percentages of qualified respondents for each (disqualified respondents not listed). Sums of workshop attendees and participants are greater than the total respondents and attendees because many participants attended and responded to surveys for more than one workshop. Similarly, sums of job roles and industry sectors for professionals are greater than 100% because several participants hold multiple job titles and/or their teams work in multiple industries. Student "industry" classified the projects, not student backgrounds. Student classes were open to all majors, but no students were design majors because UC Berkeley does not offer an industrial design degree, so those interested in the field become mechanical engineering, art, or architecture majors (the latter two were counted as "other" in the table). "Business" majors encompassed Business Administration, Information Management & Systems, Economics, and Environmental Management. "Engineering" majors encompassed Mechanical Engineering, Electrical Engineering and Computer Science, Engineering Physics, Energy Engineering, Bioengineering, Materials Science and Engineering, Chemical Engineering, Industrial Engineering Operations and Research, and Civil Engineering.

Demographic differences between the two populations obviously include age and experience. Data on professionals' age and years of work experience were not collected, but ages ranged from the late twenties to late fifties, likely averaging between late thirties and mid-forties; years of experience varied from new interns to 30 years at the same company, likely averaging 10–15 years of experience. A subtle but potentially important demographic difference between the students and professionals was the level of effort required to participate. Professionals volunteered to take time out of their workdays for workshops, preventing them from performing their normal duties, while student workshops occurred as part of classes, with no extra effort required to participate. This may have caused sample bias in the professional population, selecting for participants more interested in sustainable design than the student population. In addition, all students received 2-h workshops, as did many professionals, but 47% of professionals received 4-h workshops instead. Almost all workshop activities were the same, but in Whole System Mapping, the LCA and Decide by Priorities activities had greater depth, as did the Choose Nature's Principles activity in Biomimicry.

**2.2 Data Collection and Analysis.** Previous work described the exact workshop procedures [34]. After each workshop, professionals and students were asked to complete a survey about the workshop's design method, with these 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.)

**Table 1 Demographics**

| | Total respondents/ attendees (%) | Gender | Major/job role | Industry | Workshop responses/attendees (%) | | |
|---|---|---|---|---|---|---|---|
| | | | | | TNS | WSM | BIO |
| Student | 204/262 (67%) | M: 133 (65%)<br>F: 71 (35%) | Eng.: 163 (80%)<br>Bus.: 34 (17%)<br>Others: 7 (03%) | Transport: 39 (19%)<br>Cons. Elec.: 65 (32%)<br>Housewares: 22 (11%)<br>Medical: 21 (10%)<br>Service: 34 (17%)<br>Software: 23 (11%) | 78/118<br>(75% OR) | 133/177<br>(76% OR) | 104/144<br>(72% OR) |
| Professional | 172/258 (67%) | M: 83 (48%)<br>F: 60 (35%)<br>Blank: 29 (17%) | Design: 54 (31%)<br>Eng.: 52 (30%)<br>Mgr.: 38 (22%)<br>Sust.: 17 (10%)<br>Blank: 25 (15%) | Cons. Elec.: 68 (40%)<br>Apparel: 36 (21%)<br>Furniture: 35 (20%)<br>Housewares: 15 (9%)<br>Blank: 26 (15%) | 45/71<br>(63% OR) | 97/113<br>(86% OR) | 61/79<br>(77% OR) |

Note: Responses/attendees (%) = number of respondents followed by number of qualified participants and percent of participants responding; % OR = percent of total respondents; TNS = The Natural Step; WSM = Whole System Mapping; BIO = Biomimicry; M = male; F = female; Eng. = engineer or engineering major; Bus = business major; Mgr. = manager or executive; Sust. = sustainability specialist.



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- In your opinion, did anything in the design method provide any other value, not related to innovation or sustainability? If so, when or how?
- Would you recommend this workshop to others? If so, what would you say?
- How do you think this design method, or the ideas you got from it, will affect your product design? (Same checklist options as in pre-survey).
- Anything else you'd like to say?

These survey questions were open to any text, not multiple-choice, so all responses were qualitatively coded for mentions of the design methods, activities, or mindsets; mentions of innovation, sustainability, or other benefits; general praise or criticism of an activity or mindset or design method, and reasons why. Creswell's "concurrent nested" approach [35] was used for combining quantitative and qualitative research methods, plus Blessing and Chakrabarti's design research method #4 "descriptive study II" phase [36]. First, "open coding" classified survey responses, and then these codes were grouped into code categories for final results. For example, during open coding the quote "drawing the map of the system allows one to step back and view the entire picture" was coded "big picture," while "I think it open [sic] your mind to look closer around you" was coded "opened mind," and "broadened view of the risk and opened opportunities for solutions" was coded "broadened view." Then, as dozens of mentions were coded with these similar themes, they were all grouped into an overarching code, "broaden scope."

MAXQDA software was used to perform this coding and count code co-occurrences (overlaps). Co-occurrences were counted only once per participant, to avoid vocal minorities or percentages of respondents exceeding 100%. Answers to all questions above were then consolidated into four overarching research questions: what do students and professionals value, what do they criticize, what do they mention driving innovation, what do they mention driving sustainability. Statements were coded whenever they are related to these issues, even if the text did not fall under the specific survey question. To check reliability and avoid bias, both the lead author and a research assistant coded all 528 surveys. The coding rubric was established by the lead author; the research assistant learned the rubric by receiving 30 coded surveys for training and matching them, then coding the rest of the surveys independently. Upon checking intercoder agreement and reaching a consensus modifying codes, the final intercoder reliability had a Cohen's Kappa of 0.83 for professionals and 0.82 for students.

When analyzing data, uncertainties were calculated as binomial 95% confidence intervals using the Adjusted Wald method for improved accuracy at small sample sizes [37,38]. Differences were deemed "statistically significant" only for p-values below 0.05. Qualitative analysis of survey text searched for reasons explaining quantitative differences. Inductive reasoning was also used to check the consistency of quantitative and qualitative results.

## 3 Overall Results

**3.1 Results for Activities and Mindsets Within Each Design Method.** Surveys of professionals and students were compared by the percentage of people mentioning the different activities/mindsets of each design method. As described in Sec. 2, only one mention per person was counted, to avoid vocal minorities; analysis also did not judge intensity of value in each survey response, it only counted the number of people mentioning items. Results were split into three categories: valuing/not valuing, relating to sustainability, and relating to innovation. Reasons why respondents valued activities or mindsets were then analyzed qualitatively. All graphs below show only design practices that were mentioned by more than five respondents, thus not all activities or mindsets appear in graphs.

*3.1.1 The Natural Step.* Figure 2 shows that overall, students and professionals agree rather closely on which activities and mindsets they valued or criticized (average $p = 0.4$ across the six design practices graphed). Differences were only statistically significant for Backcasting and Decide by Priorities. Professionals valued Backcasting significantly more frequently than students ($p = 0.005$). Note that Fig. 2 does not count the enthusiasm of responses or number of mentions, only percent of respondents. Differences due to workshop duration were checked, but professionals in both workshop durations greatly valued Backcasting and Decide by Priorities (in fact, 2-h participants valued them even more than 4-h participants, but not statistically significantly), so that cause was eliminated.

Reasons listed for value and criticism were varied, and many respondents did not list them, so quantitative analysis of reasons yielded no statistically significant results for any activities or mindsets in all three design methods. However, qualitatively in The Natural Step, both populations listed similar reasons for valuing Backcasting; for example, for focusing thought by envisioning an ideal to pursue (from a professional, "Back-casting was helpful to bring ideals back to reality," while from a student, "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."). Both populations also valued Backcasting as a new lens (from a professional, "Backcasting was an interesting, innovative way to look at a problem, it helped me look at it from a different vantage point," while from a student, "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."). Both populations also valued it for business strategy benefit (from a professional, "Backcasting provided a great means to work backwards from a desired outcome. It was an interesting method for downselecting ideas based on pre-established goals and criteria," while from a student, "It is useful to think

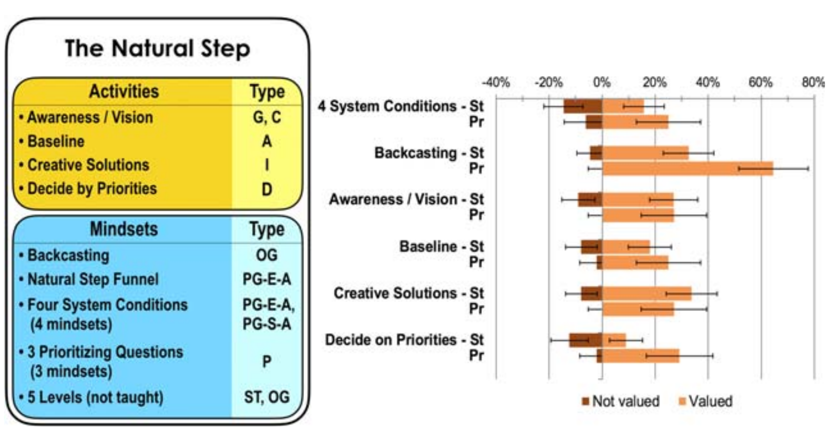


**Fig. 2 Percentage of students (n = 89) and professionals (n = 48) mentioning what they generally valued (positive %) or criticized (negative %) in The Natural Step**



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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."). Only one professional mentioned a qualitatively different reason for valuing Backcasting: ease of use ("The ABCD method [Backcasting] is a good and easy way to introduce this to our team. If this was more complex, it wouldn't spread as easily to other co-workers."). It seems likely that professionals and students mostly valued Backcasting for the same reasons, but professionals placed a higher value on those reasons because their experience clarifies the value of strategy, focus, and/or new lenses. Not enough participants of either group mentioned any reasons often enough for statistically significant comparisons.

For Decide by Priorities, again professionals valued it significantly more than students ($p = 0.04$); this difference is further supported by more students criticizing it than professionals, even if the criticism differences were not statistically significant. Both students and professionals valued Decide by Priorities for converging on practical solutions (from a professional, "selecting the most impactful ones was also valuable because it illuminated the relative values and costs of the various methods seen through EE and ME lenses," while from a student, "I thought deciding was the most useful part for my team. We were able to aggregate all of the concepts that we had come up with, and discuss which ones were actually feasible and useful."). The difference may simply lie in fewer students understanding the importance of converging on actionable solutions because the workshops occurred before the point in their class when they transitioned from idea generation to concept selection and prototyping, so they had not yet learned the importance of decision-making in design. Professionals, by contrast, are deeply aware of its importance ("prioritizing at the end, by way of vote, was important as it is unlikely product teams have the time and budget to work on everything you suggest at once."). Students also criticized Decide by Priorities for its difficulty; perhaps, it seemed difficult because they were not yet experienced in converging on solutions as professionals are ("I think the least useful was deciding. Many of our concepts were related and made sense together. This meant that it was difficult to prioritize."). Finally, some students criticized Decide by Priorities for lack of time ("The least helpful [but still interesting] portion of the workshop would have been the decision-making part. I felt that more time and research was needed to properly decide on a course of action. We were only given about 10 min to go through all of our ideas and judge them without much research which lead to half-hearted decisions and sloppy justifications for those decisions."). However, the professionals who received short workshops did not mention this criticism.

For sustainability value, Fig. 3 shows the quantitative results.

Figure 3 shows that, while students and professionals agreed that no one component of The Natural Step was significantly more useful for sustainability than any other component (all were within 95% confidence intervals of each other), far more professionals than students mentioned the Natural Step's activities and mindsets driving sustainability (average $p = 0.05$ across the six design practices graphed). Everything except Backcasting scored significantly higher for professionals than for students ($p = 0.01$ to 0.05). There may be a selection bias due to professionals being more interested in sustainable design than students; professionals volunteered to spend time out of their busy days for workshops, as mentioned in Sec. 2, while students merely attended class as usual. If this were the case, however, similar increases in responses might be observed for general value in Fig. 3, so it is unclear whether this is a driving factor.

Qualitative reasons for the increased mentions of sustainability were rarely obvious, as students and professionals largely valued similar sustainability aspects of the different activities and mindsets or were vague in their statements of value. For example, many said they valued an activity for sustainability but did not say why. In addition, some statements were precise but showed no disagreement; the Four System Conditions were valued for focusing attention on predetermined environmental and social goals the teams had not previously considered (from a professional, "This method takes into account the social side of things that is missing from LCA. This was the first time that I have brainstormed social impacts into a product where the end-user is not the person at the social disadvantage," while from a student, "Identifying the system conditions was a new idea that allowed for our team to think creatively in new ways. Categorizing different aspects of the design in regards to the environment was not something that had been a priority"). Awareness/vision was valued by both populations for focusing thought on future impacts (from a professional, "Future visioning was valuable to understand how we all thought about product sustainability attributes," while from a student, "Awareness/Visioning was very helpful for our team. We were never put into a situation where we needed to think of the extended long term consequences of our product and its environmental impact.").

As with general value of The Natural Step's components, it seems likely that professionals and students mostly found sustainability for the same reasons, but professionals placed a higher value on those reasons, possibly because of their experience. One professional comment showed that they may make mental connections between activities and mindsets that the students did not make, namely, how Baseline supports Creative Solutions ("I think more than any, the Baseline work would guide this because it allows you to really focus on where the product currently is. Without that, the concepts would be too scattered.").

For innovation value, Fig. 4 shows the quantitative results.

Figure 4 shows that students and professionals agreed on Creative Solutions being often mentioned for innovation, though not significantly more than any other activity or mindset (it was within 95% confidence intervals of others for both populations). This was

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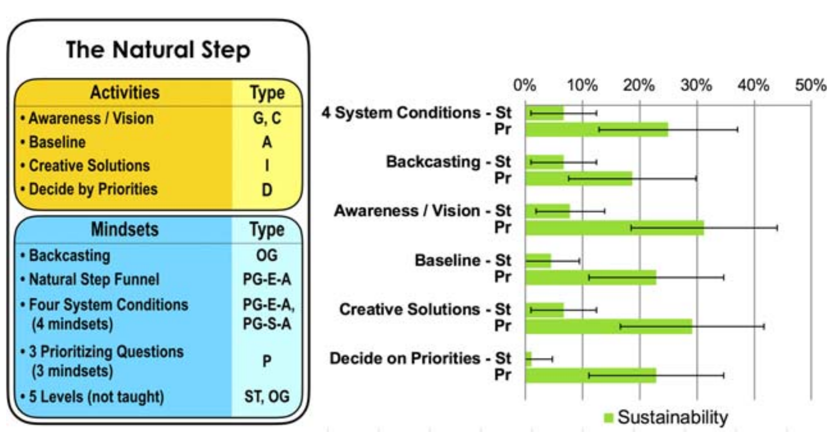


**Fig. 3 Percentage of students (n = 89) and professionals (n = 48) mentioning anything driving sustainability in The Natural Step**

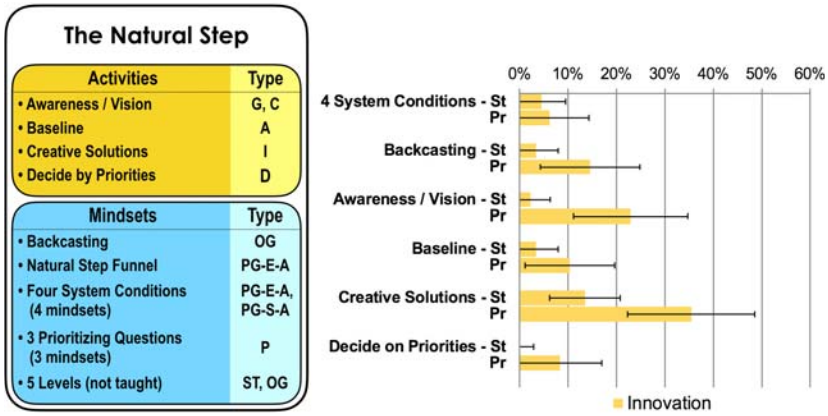


**Fig. 4 Percentage of students (n = 89) and professionals (n = 48) mentioning anything driving innovation in The Natural Step**

expected since it was the only ideation activity. However, professionals often mentioned the Natural Step's activities and mindsets driving innovation more than students. These differences were only statistically significant for Awareness/Vision ($p = 0.02$) and Creative Solutions ($p = 0.04$). These differences were checked against workshop duration, but did not correlate; in fact, more 2-h participants listed the Four System Conditions, Awareness/Vision, Baseline, and Creative Solutions as drivers of innovation (though not significantly). As mentioned earlier, selection bias might make the professional population more vocal about innovation than students because they expended more effort to participate. Again, however, if this was the case, differences like those in Fig. 4 would likely have been observed for general value shown in Fig. 2, so this seems unlikely as a driving factor, it is a more likely experience.

Qualitative reasons for the increased mentions of innovation are unclear. For Creative Solutions, both students and professionals valued it for generating many ideas or high-quality ideas (from a professional, "Loved some ideas that the team came up with and I think is worth deep diving to better understand," while from a student, "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."). For Awareness/Vision, both professionals and students mentioned it broadening their scope of ideation (from a professional, "I felt more innovative during the first brainstorm [Awareness/Vision] than when I actually reached concept stage. I suppose it was due to the fact that I immediately looked out of the box at bigger issues than those I already encounter as a product designer in a corporate company," while from a student, "In the awareness part, we realized that there were a lot of things we have not considered as part of the product development process. For instance, we did not considered the effects that our product will have for people who might not have the financial resources to afford a product like ours. That helped us start thinking of ways of how to make our product more affordable and such."). One qualitative difference was that a student mentioned Awareness/Vision simply for providing new ideas ("The visioning gave us new ideas—simplifying the product from one per desk to one per classroom") while a professional mentioned it driving radical ideas ("I like how it tells you to aim for the impossible, at first view. This open [sic] our eyes to new possibilities and innovation."). Still, this does not seem a large enough difference to alone drive the greater percentage of professionals who valued it for innovation; it is likely placing greater value on the same reasons.

In addition to the two statistically significant differences for innovation in The Natural Step, another difference may be instructive despite not being significant: for Decide by Priorities, no students mentioned it driving innovation, whereas 8% of professionals did. The professionals valued it for prioritizing ("The post-it board was valuable and working through the decide section put it all into perspective and we were able to recognize some low hanging fruit that we can action on now") and even for generating new ideas ("Deciding at the end came up with surprising solutions."). This may again be due to students not yet having learned decision-making in their design class.

To summarize, student results predicted which activities or mindsets in The Natural Step were valued by professionals for sustainability and innovation, since none stood out in either case, though professionals mentioned everything driving sustainability and innovation more often than students. There were two places where student results failed to predict professional results. First, students did not greatly value any one activity or mindset overall, whereas professionals clearly favored Backcasting. Second, Decide by Priorities was valued by professionals for sustainability, innovation, and overall, but it was barely valued by students. This could be due to all students receiving the workshops before learning about decision-making in their design class, thus not yet appreciating its importance, but this difference did not appear for the decision activity in Whole System Mapping.

*3.1.2 Whole System Mapping.* Comparison of professional versus student results for Whole System Mapping is shown in Fig. 5. Note that participants from both populations wrote "priorities" instead of "Prioritized Design Spec" as shown in Fig. 5 (left) literature analysis; therefore, it will hereafter be referred to only as "Priorities."

Figure 5 shows that while the agreement was relatively high overall (average $p = 0.2$ for all seven design practices graphed), including agreement on the most often valued design practice (Draw System Map), there were also several statistically significant deviations: Systems Thinking, LCA, Brainstorm to Eliminate and disvaluing Brainstorm to Eliminate.

Students and professionals valued Draw System Map significantly more often than any other activities or mindsets ($p = 0.002$ for students, 0.0005 for professionals). Both valued it for broadening scope (from a professional, "Drawing the map of the system allows one to step back and view the entire picture," while from a student, "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."). Both groups also valued it for focusing thought so the whole system is mentally manageable (from professionals, "Breaking down the system into different components helped make the thought process more approachable," while from students, "Seeing the map drawn out helped with understanding the big picture and how everything is connected."). Professionals also valued it for collaboration ("Mapping out helped think through every aspect of the product. Thinking it through with others helped get lots of ideas and we really built off each other's ideas.").

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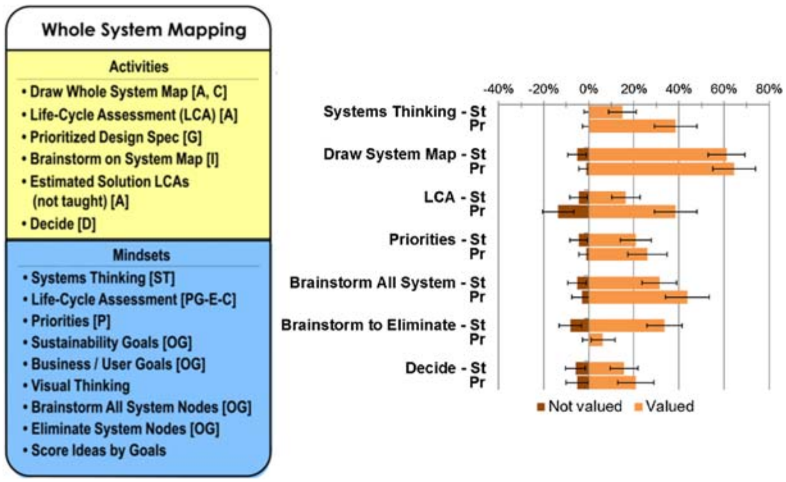


**Fig. 5 Percentage of students (n = 134) and professionals (n = 96) mentioning what they generally valued (positive %) or criticized (negative %) in Whole System Mapping**

LCA was more valued by professionals than by students ($p = 0.006$); this was not due to workshop duration, because professionals in 4-h and 2-h workshops valued LCA similarly. LCA was valued by both students and professionals for focusing or clarifying thought on sustainability (from professionals, "It was interesting to see how the perceived impact of things might actually be very different from the actual impact," and from students, "It also helped figure out where the biggest impact on the environment would be in the life of a product."). Professionals seemed more attuned to where LCA would correct their misperceptions or help them test tradeoffs between choices; students did not mention such subtleties. LCA was also often criticized, sometimes by the same people who valued it, in both versions taught. In short workshops (showing pre-calculated slides), it was criticized for being too general ("The scoring system seemed a bit arbitrary without having data to back it up"), while in long workshops (estimating LCA of the actual product), it was criticized for being difficult ("LCA software seems too difficult to use/deal with.").

Systems Thinking was also more valued by professionals than by students ($p = 0.003$), but without clear reasons. It was commonly valued by both populations for broadening scope (from professionals, "Recognizing that a more optimal solution may not be at the level of material choice or product configuration, but the service or context of the product in the overall system," while for students, "It was good to think of the whole scheme of our product from material to final product as well as the use cases from our users.").

Brainstorm to Eliminate provided a surprise—students mentioned it much more than professionals ($p = 0.00005$), but it is unclear why. It was not a named activity but a mindset applied to Brainstorm on System Map, so perhaps professionals more closely followed the names of activities in Fig. 1, while the students paid less attention to formalities. Both populations valued it for broadening the scope (from professionals, "Having to fill the entire map with ideas forced our team to think deeper" or "Brainstorming improvements AFTER mapping the whole system is a powerful way to find opportunities that go beyond the usual methods," while for students, "I think good old-fashioned brainstorming is good, too, but this is useful when we have one product/concept in mind, and we need to expand and think about features and how to improve for future iterations."). Both groups also valued it for novelty (from professionals, "Skipping a step was a novel approach to brainstorming," while from students, "Eliminating system nodes was also a very different, very effective perspective in looking at our problem."). Both groups also valued it for simplifying their designs (from professionals, "looking at baseline Bill of Materials to see what elements we could combine or eliminate seemed valuable. This lead [sic] to reduction in cost and improved sustainability numbers," while from students, "Eliminating System Nodes really helped force our group to see what we don't need in our overly complicated water bottle."). It is possible that students found this simplification more valuable than professionals because they were still in ideation phases, before having converged on designs or manufactured anything, unlike most professional teams; however, this is purely speculation, there are no survey quotes to support it.

For sustainability value, Fig. 6 shows the quantitative results.

Figure 6 shows much disagreement between student and professional mentions of sustainability (average $p = 0.09$ for all seven practices graphed). Professionals valued LCA, Priorities, Brainstorm All System, and Decide significantly more often than students for sustainability ($p = 0.0002$, 0.004, 0.008, and 0.002, respectively) but valued Brainstorm to Eliminate for sustainability significantly less ($p = 0.0005$). The largest difference was for LCA ($p = 0.0002$); this is likely attributable to workshop duration differences since this was the one case where professionals listed valuing something statistically significantly more in 4-h workshops ($53\% \pm 15\%$) than 2-h workshops ($24\% \pm 11\%$). Both professionals and students valued LCA for sustainability for similar reasons (from professionals, "The mindset of using life cycle analysis to determine the most effective ways to increase sustainability were probably the most helpful in improving product sustainability in this example," while from students, "Life cycle assessment was useful to our team as we were able to assess the full production cycle and how the end product would end up being disposed of."). However, the longer workshops performing LCA calculations on the specific products enabled more correction of preconceptions and more testing of tradeoffs between choices ("the ability to test or estimate the impact of independent variables. Side by side comparisons."). While these did not change mentions of overall value of LCA, they greatly changed the mentions of sustainability value.

The difference for Priorities is likely partly due to duration and its link to LCA; however, duration did not cause a statistically significant difference for professionals, so other factors must be involved here. As mentioned earlier, students were still in ideation phases, before having converged on designs or manufactured anything, so they were likely less aware of the importance of prioritization and converging. Qualitative analysis supports this: professionals mentioned links between priorities and results ("the best part is to deciding [sic] the priorities, the rest just followed them" or "After looking at the impacts of the current material and design configuration, I enjoyed prioritizing the quality, cost, and environmental impacts—as these are often related, but not often recognized as



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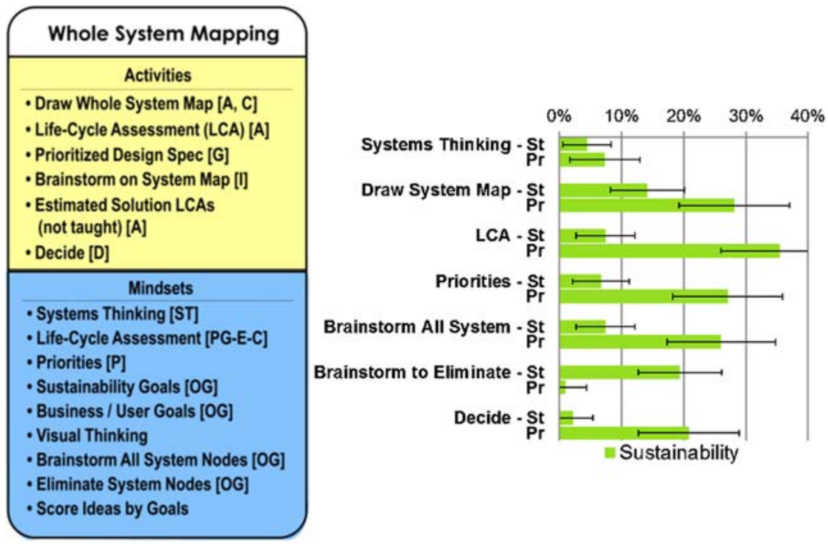


**Fig. 6 Percentage of students (n = 134) and professionals (n = 96) mentioning anything driving sustainability in Whole System Mapping**

such. This, I believe, allows for more ideas to be pursued, as the sustainability can help catalyze cost solutions and vice versa [when applied correctly].”). Students did not make these connections, which appear to come from practical experience.

Figure 6 also shows that professionals valued Brainstorming All System for sustainability more than students ($p = 0.008$) but the opposite was true for Brainstorm to Eliminate ($p = 0.0005$). Reasons for this are unclear, as was discussed above concerning the general value of Brainstorm to Eliminate. One hypothesis was that because Brainstorm All System Nodes and Eliminate System Nodes were two mindsets used during the same activity (Brainstorm on System Map), respondents tended to mention one or the other, not both. However, this trend only holds for innovation, not general value, so it seems unlikely.

For innovation value, Fig. 7 shows the quantitative results.

Figure 7 shows decent agreement between students and professionals, both in terms of overall similarity (average $p = 0.4$ for all seven practices graphed) and in agreeing about two of the three most often mentioned design practices (Draw System Map and Brainstorm All System). The only significant difference between professionals and students was that professionals mentioned Brainstorm All System for innovation even more than students ($p = 0.03$), distinguishing it from Brainstorm to Eliminate, unlike students. Both populations valued Brainstorm All System for broadening scope (from professionals, “The brainstorming process gave me time to look at nonproduct innovations that would improve the process sustainability,” while from students, “Our group managed to come up with a good new solution for each category branching from our main device, and some were brand new, even though we thought we were in a rut. That was pretty great.”). One hypothesis for professionals’ greater valuing of Brainstorm All System was that it provided an escape from their daily routine of specialization in only one part of the system. Students have not yet experienced corporate work’s hyper-specialization and so do not see that value. Brainstorm to Eliminate does not provide this value.

To summarize, student results adequately predicted which activities or mindsets in Whole System Mapping were valued for innovation, and for overall value predicted four of seven items, both in terms of the most-valued practices and the percentages of people mentioning each practice. They even predicted that while the activity most valued in Whole System Mapping is Draw System Map, it did not score highest for sustainability or innovation; instead, much of its value was for the general design process, such as collaboration. However, professionals and students largely disagreed on

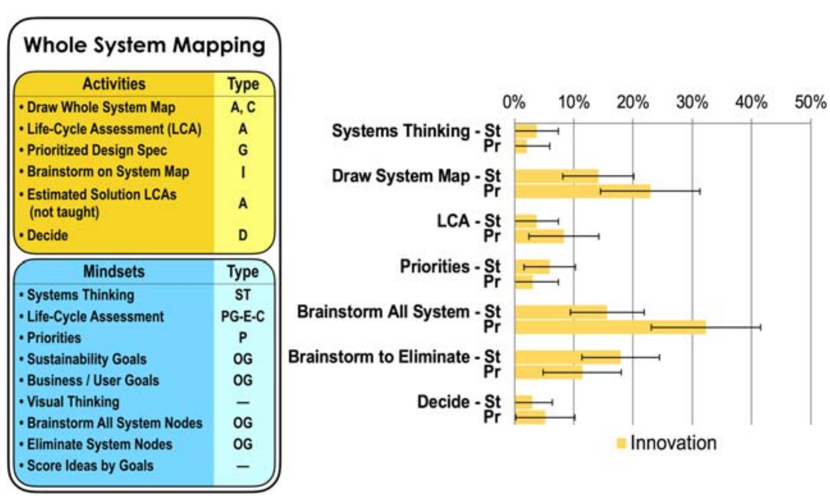


**Fig. 7 Percentage of students (n = 134) and professionals (n = 96) mentioning anything driving innovation in Whole System Mapping**



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sustainability value, with a much higher percent of professionals valuing nearly everything, and a slightly different distribution of the most valuable practices. These differences may be due to sampling bias since professionals expended effort to volunteer for the study and thus may have been more committed to sustainability. Some professionals' longer workshops also made them value LCA more for sustainability; this was the only significant difference by duration in all three workshops.

*3.1.3 Biomimicry.* Comparison of professional versus student results for Biomimicry is shown in Fig. 8. Note that participants wrote "AskNature.org" instead of "Discover Model Strategies Online" as shown in Fig. 8 (left) literature analysis, so "AskNature.org" is used from here forward.

Figure 8 shows that for Biomimicry student results were reasonable predictors of professional results in an absolute sense (average $p = 0.4$ for all seven comparisons graphed), with significant disagreements occurring only in Nature as Mentor and Translate to Buildable Things ($p = 0.008$ and $p = 0.02$ respectively). However, professionals clearly favored Nature as Mentor and AskNature.org over other activities and mindsets ($p = 0.0002$ and $p = 0.04$, respectively, versus the next highest rated activity, Define Problem Biologically), which students did not. Nature as Mentor was barely criticized by either group (never by professionals and by 1% of students), but AskNature.org was criticized by students. However, this was largely for slowness on one particular day, perhaps due to campus internet trouble. This may help explain its lower percentage of value from students, but would not explain Nature as Mentor. Thus, overall, students did not predict which components of Biomimicry would be most valued by professionals.

For Nature as Mentor, professionals and students both valued it for the same reason: providing a new lens (from professionals, "using a new perspective—through looking at nature—to re-inspire challenges that seemed impossible," while from students, "Nature as a mentor is definitely a concept that I am not used to seeing or thinking about, and it helped me realize why so many product features are the way they are, and opened my eyes to innumerous opportunities in the market in various industries."). Professionals and students also both valued AskNature.org for providing a new lens and enjoyment (one professional called it "animal Facebook"), but again, professionals mentioned it more often. Perhaps professionals simply valued this quality more than students because students were new to the design process in general and thus had many sources of novelty relative to their experience.

Students valued Translate to Buildable significantly more than professionals and had a qualitatively different reason: they valued it for enjoyment and innovation ("I also really enjoyed 'translate ideas into buildable things' in that it got the creativity juices flowing."). Professionals simply valued it for practicality ("The ability to manufacture section made you really analyze whether or not the natural solution to a problem could be manufactured in a reasonable method. Great segment of this workshop!"), This was surprising, since students and professionals agreed about enjoying Models in Life and AskNature.org. Another possible explanation for the difference in value is that professionals constantly consider how to translate ideas into manufacturable products, while students had not yet reached that stage of the class.

For sustainability value, Fig. 9 shows the quantitative results.

Figure 9 shows that professionals and students agreed on what drives sustainability in Biomimicry—there was no statistically significant difference for any of the seven activities or mindsets ($p > 0.2$ for all and average $p = 0.6$). Thus, in this case, students were an excellent predictor of professional opinions. Note that this may be due to unusually few professionals valuing anything in Biomimicry for sustainability compared to The Natural Step or Whole System Mapping; in all three design methods, students had similarly low rates of mentioning sustainability-related practices, but professionals only agreed for Biomimicry.

For innovation value, Fig. 10 shows the quantitative results.

Figure 10 shows that, as with overall value, students predicted professional results well for absolute scores of what drives innovation in Biomimicry (average $p = 0.5$ for all practices graphed), but failed to predict the important result: professionals clearly valued AskNature.org the most for innovation ($p = 0.04$ versus the next-highest activity, Models in Life), but students did not. The difference was also qualitative: students never mentioned why AskNature.org drove innovation ("I think the website to find the solutions to nature gave us an opportunity to look for innovative solutions for problems"), whereas professionals said it drove innovation by broadening scope ("Online resources have much more biological detail than our team could generate on our own.").

To summarize, student results did not predict which activities or mindsets in Biomimicry were most valued overall or for innovation by professionals. Professionals clearly most valued Nature as Mentor and AskNature.org overall, and AskNature.org for innovation, while student results were dispersed. Student results did, however, predict professional opinions of sustainability in Biomimicry's activities and mindsets, with none mentioned particularly often. This differs from The Natural Step and Whole System Mapping, where professionals mentioned valuing most activities and mindsets for sustainability far more than students.

**3.2 Results by Activity Category.** To determine if students and professionals reacted similarly to entire categories of design activity (such as ideation, goal-setting, etc.), regardless of what

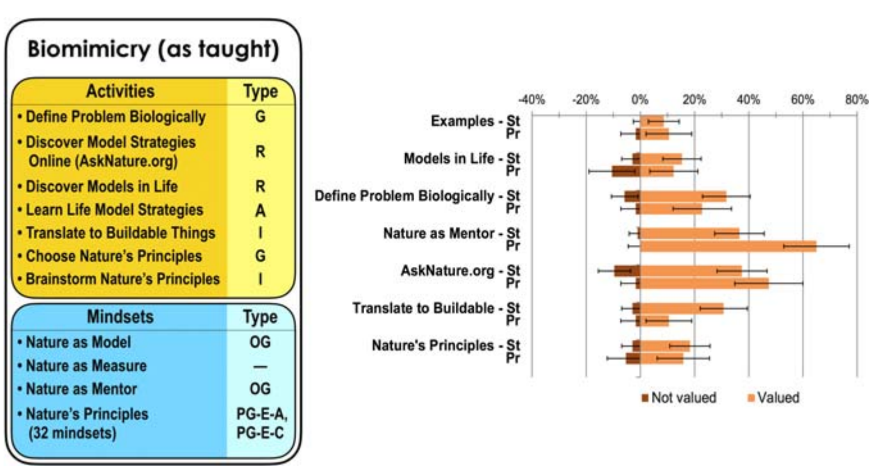


**Fig. 8 Percentage of students (n = 104) and professionals (n = 57) mentioning what they generally valued (positive %) or criticized (negative %) in Biomimicry**



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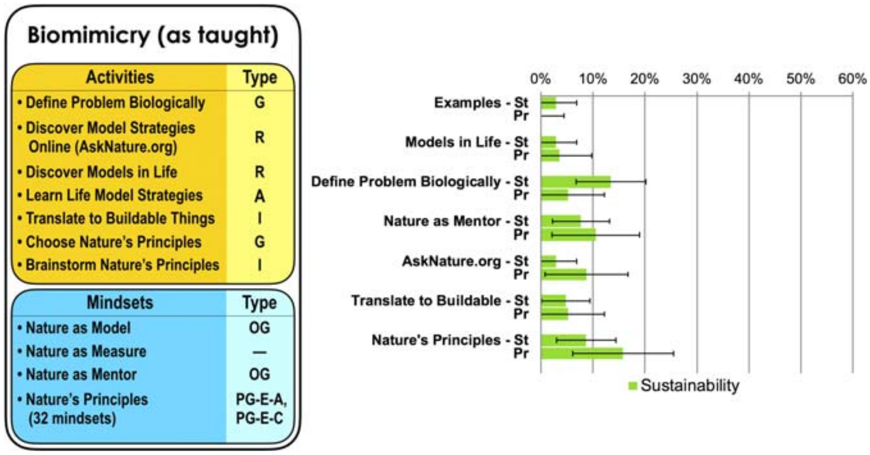


**Fig. 9 Percentage of students (n = 104) and professionals (n = 57) mentioning anything driving sustainability in Biomimicry**

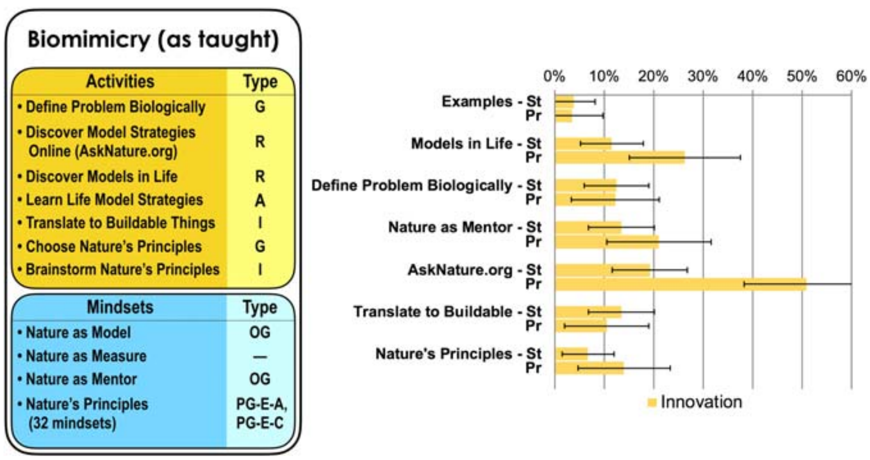


**Fig. 10 Percentage of students (n = 104) and professionals (n = 57) mentioning anything driving innovation in Biomimicry**

design method the activities come from, mentions of activities from all three design methods were combined by category (see Fig. 1). The Research category included Biomimicry's AskNature.org and Models in Life. The Analysis category included The Natural Step's Baseline, Whole System Mapping's Draw System Map, and LCA. The Ideation category included The Natural Step's Creative Solutions, Whole System Mapping's Brainstorm All System, and Biomimicry's Translate to Buildable and Nature's Principles. The Build category had no activities or mindsets from any of the methods (an indication they should be combined with traditional design methods such as Human-Centered Design). The Communicate category included The Natural Step's Awareness/Vision and Whole System Mapping's Draw System Map. The Decision category included The Natural Step's Decide by Priorities and Whole System Mapping's Decide. The Goal-Setting category included The Natural Step's Awareness/Vision, Whole System Mapping's Priorities, and Biomimicry's Define Problem Biologically and Nature's Principles.

Figure 11 shows that student results predicted professional results well for overall value (average $p = 0.6$ across the seven categories, including all 20 activities from the three design methods). No differences were statistically significant for individual categories, and neither population showed a significant favorite or most criticized category. It is possible professionals valued Analysis and Decision more than students, but not significantly. The Communicate category scored highly with both groups, primarily due to the high score of Draw System Map as shown in Fig. 5, but it was not valued significantly more than most others for either population. Decision activities were not often valued by students; as mentioned in the discussion under Fig. 2, there are no clear reasons for this from participant quotes, but one speculation is that students did not yet fully understand the importance of decision-making in the

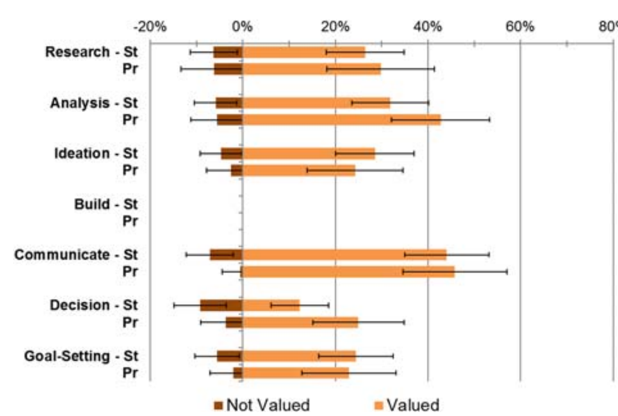


**Fig. 11 Percentage of student (n = 327) and professional (n = 201) responses mentioning the different categories of activities or mindsets from all three design methods that they generally valued or did not value. Note none of the three design methods contained Build activities.**



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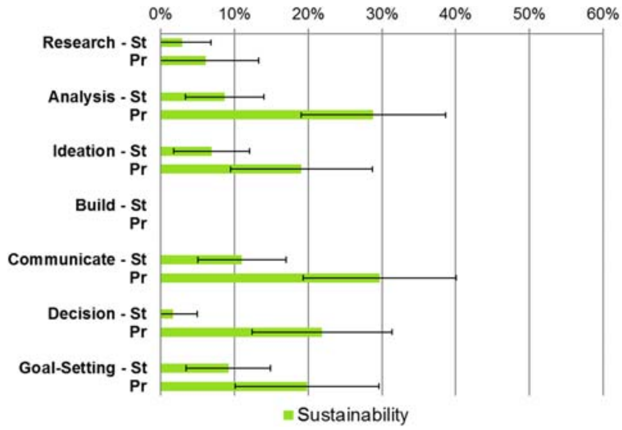


**Fig. 12 Percentage of student (n = 327) and professional (n = 201) responses mentioning any category of the activities or mindsets driving sustainability**

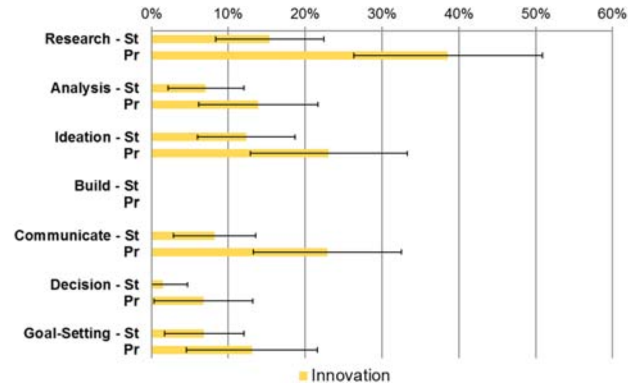


**Fig. 13 Percentage of student (n = 327) and professional (n = 201) responses mentioning any category of the activities or mindsets driving innovation**

design process because they had not reached that stage of the course yet. Finally, note that none of the activities in the green design methods studied are Build activities. The category was still included in the graph because it is a vital stage of product development. However, because it is lacking in the design methods discussed, it must be supplied by combining these with other design practices, as mentioned earlier.

Unlike for overall value, students and professionals disagreed about sustainability value of activity categories, as Fig. 12 shows.

Figure 12 shows mixed results: student results largely predicted professionals' lack of favorite category for sustainability, though students failed to predict professionals' low score for Research and instead scored Decision low. Students also did not predict absolute percentages of mentions for several categories: professionals mentioned significantly more sustainability value in Analysis ($p = 0.01$), Communicate ($p = 0.03$) and Decision ($p = 0.005$) categories. As mentioned earlier, however, there may be selection bias of professionals being more committed to sustainability overall, because volunteering for workshops required effort for them but not for students.

The Decision category showed the most dramatic difference, and the difference came from both of its activities: The Natural Step's Decide by Priorities in Fig. 3 and Whole System Mapping's Decide in Fig. 6. As speculated earlier, students may not have understood the importance of decision-making due to the workshops occurring before their class taught decision-making.

For innovation value, students and professionals also had mixed results, as Fig. 13 shows.

Figure 13 shows that student results predicted professional responses to what activity categories most drove innovation, but neither student nor professional results had a strongly significant favorite. Research, Ideation, and Communication may have been professional favorites, but innovation value was fairly dispersed; student response differences were even more dispersed, thus lacking strong predictive value. Professionals listed everything driving innovation somewhat more often, but not significantly so. Only the Research category was significantly different ($p = 0.02$), due to professionals valuing AskNature.org more, as shown in Fig. 10. Even there, both groups agreed on it being most frequently mentioned, and both groups valued it for similar reasons, as quoted earlier. Both groups also agreed on seldom mentioning Decision activities for innovation, as described after Figs. 4 and 7. Therefore, students may act as a reasonable proxy for professionals in testing what drives innovation in design methods, but such predictions may be weak.

To summarize, student results did not usefully predict which categories of activities or mindsets were most valued by professionals overall or for innovation or sustainability. However, this is at least partly due to the lack of significant differentiation between the different categories by either professionals or students. If any category were truly outstanding for overall value, sustainability, or innovation, it might be outstanding for students as well as professionals.

**3.3 Results by Demographics.** Results were also analyzed by demographic, to see if subsets of each population matched better than the overall populations. Analyses by job role/major, industry, gender, student class year, and industry-sponsored student project versus independent student project were all negative. In a few cases, p-values were below 0.05, but this was inevitable given the over 2000 comparisons, and none showed clear qualitative reasons to support them.

## 4 Limitations

Some limitations that could be addressed by future studies include testing a larger number of design methods, testing more participants across more industry categories, and requiring tighter matching between student and professional conditions. Testing more methods might provide more generalizable results, particularly for categories of design activities. Requiring students to volunteer outside of class to match professional conditions would have drastically reduced participation, but could have eliminated possible selection bias of professionals being more interested in sustainability (though these professionals did not have more sustainability expertise than the students, and many student studies are likely to use full classes, so this tested a realistic condition). Offering only one workshop duration could improve results slightly, as the different durations caused different results in one activity of one design method (Whole System Mapping's LCA). Finally, testing more participants would reduce uncertainty and might show differences not apparent here, including possible differences by demographics.

## 5 Conclusions

Students are easily accessed for testing but lack practical experience which industry depends on. The aim of this paper was to determine whether student reactions to sustainable design methods can predict professional reactions, in workshops of three design methods. Because professional participants were volunteers but student participants were entire classes, the absolute values were not expected to be similar, and indeed, professionals reported more overall value and sustainability value in almost all components of all three design methods. The hypotheses were that students could predict: (A) which components of each method provided the most and least overall value; (B) which components provided the most and least sustainability value; and (C) which components

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provided the most and least innovation value. Reasons why they were valued could not be quantified with statistical validity but provided qualitative insight.

Quantitatively, results did not strongly validate these hypotheses: For overall value, student results only predicted what professionals most valued in one of three cases, Draw System Map in the Whole System Mapping method. In Biomimicry, the professional favorites (a combination of Nature as Mentor and AskNature.org) were similar in students but not statistically significant. In The Natural Step, the clear professional favorite showed no notable student preference. Professional and student results agreed on a lack of statistical significance in least-favored components. Decision activities across methods were valued especially infrequently by students when compared with professionals, perhaps because their workshops occurred before decision-making was taught in their design class.

For innovation and sustainability, student results predicted professional results reasonably, but perhaps only because both results were largely distributed, without striking winners or losers. In the one case where professionals did report a striking favorite innovation activity (Biomimicry's Asknature.org), student results failed to predict it. For sustainability value, the only method where strong preferences appeared (Whole System Mapping) showed students and professionals disagreeing. Students did predict professionals' overall lower sustainability ratings for Biomimicry activities and mindsets compared to those in The Natural Step and Whole System Mapping.

Qualitatively, however, students' reasons for valuing design activities and mindsets usually agreed with professionals, for all three design methods. Thus, students may still be useful to predict why professionals will value different design activities or mindsets. For example, if professionals desire an activity for strategic thought or for envisioning ideals to pursue, they could see students valuing Backcasting for these reasons, and choose it accordingly. This does not predict the amount of value but might predict kinds of value.

To summarize, this study found that when empirically testing the components of these sustainable design methods on existing design projects, student responses did not strongly predict where professionals would find the most overall value, sustainability value, or innovation value quantitatively. Thus, student studies may not help choose how to combine or streamline sustainable design methods in real-world contexts, since maximizing performance likely requires knowing the most-valued activities or mindsets of each design method. However, student results did strongly predict why professionals valued the activities and mindsets, which may still be useful for combining or streamlining design practices in the sense of choosing the right tools for the jobs at hand. While more research is required, this result will hopefully help researchers choose their study participants to balance convenience against the kinds of questions asked to drive sustainability in design.

## Acknowledgment

Thanks to Mohamed Helayhel for his editing assistance. This work was based on data from earlier research partially funded through US National Science Foundation Integrative Graduate Education and Research Traineeship grant #1144885.

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