What Role Do Tangibles Play in Fostering Design Thinking Skills? An Exploratory Study

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Abstract*— Despite the importance of using artifacts during the design thinking process, there is a limited understanding of the influence of tangibles with lower perceptual richness on design thinking skills within educational settings. It is speculated that tangibles may ease the visualization and communication of ideas, enhance interactions and collaboration, as well as create a playful experience for participants. With imposing external constraints, tangibles can help students prioritize and focus on essential elements in communication and developing narratives around their proposals, and create a relatively simple platform for thinking and reasoning through different perspectives, replicating what designers do in real-world practice. We initiated a study to explore the use of tangibles in a graduate-level management course at a technical university in Switzerland. Three different tangible activities, using LEGO bricks, were incorporated during earlier phases of the design thinking process, and student groups were encouraged to take advantage of the tangibles. Employing a qualitative case study approach, this study explored the influence of using tangibles concerning design thinking characteristics. While most students demonstrated engagement, collaboration, and playfulness during the activities, the results showed that the explicit benefits of tangibles depend on the type of activity and group dynamics. The primary benefit reported was when students worked on developing problem statements where they co-created meaning by manipulating LEGO pieces. The use of tangibles not only helped students with visualization and communicating ideas; it added flexibility for exploration as ideas emerged through conversational and material practices. Specifically, the findings demonstrated the benefits of tangibles concerning two traits of design thinking: experimentalism and collaboration. In this paper, we elaborate on the underemphasized role of tangibles concerning transversal skills and point out critical criteria for developing and incorporating tangible activities within higher education settings. Reflecting on the results, we argue that using tangibles can facilitate developing collective understanding.

Keywords—design thinking, tangibles, collaboration, playful learning, systems thinking

I. Introduction

Adequate preparation of professionals to deal with the complex and ambiguous nature of the problems in today's world has been at the center of attention in higher education settings in the last two decades. Within engineering education, there is a strong emphasis on problem-solving and applying engineering design skills considering broader social factors, as spelled out in desired learning outcomes identified by different accreditation bodies, for instance, the Accreditation Board for Engineering Technology (ABET). While there is no doubt about the primacy of problem-solving in the engineering profession, the ways by which engineers, and other professionals, would (and should) approach problem-solving has been the subject of debate in different bodies of literature, notably business and management. Inspired by the ways by which designers think and work, competence in design thinking is now considered essential for professionals in addressing complex situations [1]-[3]. Illustrations of design thinking have often emphasized a human-centered, user-driven approach to developing creative and innovative ideas, products, and services [4], [5]. Mediums for teaching design thinking create experiential learning opportunities where diverse group of students can tackle authentic problems; they move through iterative design thinking process to build empathy for users, redefine a given challenge, develop ideas, prototype and test their proposals [1], [6]-[8]. Various tools and techniques can be used to support the design thinking process, among which tangibles can facilitate visualization as well as conversation and feedback through prototyping [4], [5], [9]. There is considerable evidence that practitioners do take advantage of tangibles, for instance, card-board or LEGO, to support the design process [5], [10]; however, when it comes to educational settings there is underrepresentation of studies. The purpose of this study was to explore the benefits and challenges of using tangibles offered to students in a graduate-level design thinking course at a technical university in Switzerland.

Before addressing the potential benefits of tangibles in connection with design thinking skills, we shall clarify what is striking about design thinking and describe the characteristics of a design thinker. The conventional step-by-step design process, with definite conditions, in which designers merely rely on "technical rationality" and existing rules and principles for problem-solving has shown to be inadequate in dealing with uniqueness, complexity, uncertainty, and conflicting values in given situations [3], [11]. The design profession became a source of inspiration; reflecting on how designers think and work in dealing with illformulated problems with conflicting values, scholars pictured processes, methods, and mindsets professionals, managers or engineers would need to approach problem-solving. Through this discourse, the concept of design thinking has emerged.

While there are several conceptual perspectives on design thinking, for instance, creation of artifacts, reflexive practice, problem-solving activity, a way of reasoning/making sense of things, and creation of meaning [12], and, in general, there is a lack of consensus about its definition [12], [13], scholars identified similar characteristics of design thinking. Reviews of theoretical perspectives and practice of design thinking pointed out three stages of need finding and problem definition; ideation; and prototyping [9], [14]. As a way of thinking and reasoning, design thinking combines inductive, deductive, and abductive reasoning [1]. What is essential in the design profession, which has been underemphasized in science and engineering, is abduction, where designers need to create objects, services, systems or processes addressing a desired value, often in the absence of initial governing principles [15]. In doing so, they need to move back and forth between problem space and solution space and construct a new perception, a different way of framing the problem, considering its broader context [3], [15].

Scholars identified skills and traits connecting to design thinking by mapping the nature of design practice. Brown, in a widely recognized article on design thinking [4], described five characteristics of design thinkers: (1) empathy, (2) integrative thinking, (3) optimism, (4) experimentalism, and (5) collaboration. Empathy is the ability of a designer to imagine from multiple perspectives. Considering the human-centered nature of design thinking, the primacy of imagining what others experience and understanding other perspectives has been highlighted by other scholars (e.g., [1], [9]). Integrative thinking is the ability to think holistically beyond analytical modes of reasoning. Optimism is the perseverance of the designer despite complexity and challenges and assuming at least one potential solution better than existing alternatives. Experimentalism highlights creative and innovative ways of defining and experimenting new solutions. Lastly, collaboration is the ability to work with individuals with diverse backgrounds. In the context of engineering design, more specifically, Dym et al. [2] emphasized five skills associated with characteristics of design thinking: (1) ability to tolerate ambiguity and handle uncertainty, (2) big-picture thinking, (3) thinking as part of a team in a social process, (4) thinking and communicating in several languages of design, and (5) ability to handle uncertainty and think in terms of the big picture. Some overlap exists between the two groups of skills identified, Coleman et al. [16] cross-referenced the two sets of traits; however, critical analysis of similarities and differences is beyond the scope of this paper.

Within engineering education, several empirical studies investigated students' design thinking skills. Coleman et al. [16] examined the perceived design thinking ability of nationally represented senior engineering students and first-year students interested in engineering in the U.S. using a design thinking instrument developed by Blizzard et al. [17] based on Brown's traits of design thinking. Considering the complexity of capturing empathy, the proposed survey focused on feedback-seeking. Coleman et al. [16] explained some of the instrument's limitations, but what is important is that senior engineering students' perceived design thinking skills were significantly lower than first-year students interested in engineering. The two traits where senior students had significantly lower scores were: experimentalism and feedback-seeking. The authors speculated that the lack of opportunities for students to divergent thinking and practice design with users in mind, user-centered design, during the undergraduate study may explain the findings [16]. Similar concerns have been raised by other scholars. Atman et al. [18], in an in-depth study of comparison of first-year and senior engineering students approaching open-ended problems, reported that some senior students started with one design modifying existing alternatives rather than developing multiple solutions. Daly et al. [19] argued about the general tendency of fixation in engineering and the importance of idea generation techniques to support divergent thinking. Regarding the role of empathy in design, Zoltowski et al. [20] interviewed 33 engineering students with various design experiences. Students' experiences were categorized into seven qualitative ways depicted on two axes "Understanding of the Users" and "Design Process and Integration". Among participants, some senior students showed a lack of user appreciation. The authors argued that learning more about design will not necessarily lead to experiencing human-centered design, and students would need to be better motivated, internally or externally [20].

Overall, formal training and practice in the design thinking process appears to be essential in enhancing students' design thinking skills; and further, scaffolding pedagogical activities at earlier stages of design thinking, i.e. need finding and ideation, appears to be critical, considering the reported shortcomings and the primacy of earlier stages as foundation for developing innovative ideas [21]. While there is less evidence on students' design thinking ability at graduate-level, it is reasonable to speculate that potential limitations and lack of preparation of students may continue during graduate studies. This is in particular plausible in case of lack of exposure to interdisciplinary education.

II. Design Thinking and Tangible Objects

Tangible objects are used extensively to help develop conceptual and procedural knowledge in various educational settings. Within science and engineering education, educators often rely on representations or real-world objects to help students in the process of learning. Tangibles provide visualization and help students understand abstract concepts and principles through representation, manipulation, and active engagement. Prior studies examined the benefits of using physical manipulatives to improve motivation and enhance conceptual understanding [22]-[24]. Conceptually, the benefits of incorporating manipulatives in learning can be explained by embodied cognition and sociocultural perspectives of learning, where cognition is viewed in interactions with body and the environment [25]-[27].

With growing interests in game-based learning and playful pedagogy, and the application of tools that support the meaning-making process and collaboration, such as Lego Serious Play (LSP), there has been increasing attention to the potential influence of tangibles on students' transversal/professional skills. Concerning design thinking in practice, it might seem evident that tangible objects can help professionals visualize and materialize ideas at the earlier stages of design thinking and provide artifacts for rough prototyping to facilitate feedback and communication about the concepts/ideas, and in general, serve as "common reference" [28] for individuals with/without similar backgrounds. Brown [5] described a case where IDEO worked with a group of surgeons to develop a new device for sinus surgery, where a designer made a rough prototype, taping a whiteboard marker, a film canister, and a clothespin as the surgeons were describing their ideal instrument.

Tangible objects that provide low fidelity representations, with lower perceptual richness, e.g., LEGO bricks, support visualization and rough representation of ideas and can serve as a springboard for discussion to improve the design at the earlier stages of design thinking [4] [5], [8], [10]. In an investigation of the use of different design methods by novice multidisciplinary teams in addressing semester-long projects on developing new product concepts, Seidel and Fixson [8] reported that high-performing teams regularly used prototyping during both the concept generation and concept selection phase and benefited from opportunities for combining brainstorming and prototyping. Here, it is critical to make a distinction between representing an object or product using low fidelity manipulatives/artifacts where parts of a design and its functional elements are created through incomplete models/representations, see for instance [29], [30], and when personal meanings are assigned to pieces of manipulatives and tangibles that do not objectively represent one specific thing. Nevertheless, material practices and conversational practices, e.g., the use of metaphors and stories [28], support the construction of new understandings. Material practices facilitate quick capture and representation of ideas (sharable with others), comparison and bridging ideas, and making changes into and building on different ideas that can result in developing new interpretations and understanding [28]. These effects can be operational independent of the degree of abstraction and fidelity.

Given the importance of visualization in design thinking, particularly in earlier phases of the process [6], and of using material representations, along with conversational practices, e.g., use of metaphors and stories, in students' engagement during individual and collective sensemaking process [6], [28], [35], we speculate the potential benefits of using tangibles in educational settings.

Furthermore, incorporating tangibles can create a playful experience for participants where (i) boundaries with the real world become unclear, and (ii) there is more flexibility to try new things and adopt different perspectives. Although it cannot be categorized as free play, a tangible activity may address the same playful elements: enjoyment, internal motivation, internal reality, and interactivity [31]-[33]. Whitton [34] examined playful learning in higher education, addressing three major characteristics: intrinsically motivated, immersive, and positive construction of failure. Individual attributes, design, and facilitation of an educational intervention play a significant role in the impact of playful experience; however, it is reasonable to speculate that tangible activities may help students immerse themselves in the experience, invent and apply new rules in the process of experimenting and interpreting new ideas.

As noted earlier, this study was defined in the context of a graduate-level design thinking course at a technical university exploring the influence of using tangible objects, in this case LEGO bricks, on design thinking skills.

III. Reserch Design

This research study employed a qualitative case study approach to explore the influence of using tangibles during the design thinking process. The central research question was: Whether and how does the use of tangible objects with low perceptual richness at earlier phases of design thinking influence students' design thinking skills? Considering the lack of empirical studies in the areas of investigation in educational settings and the number of various potential variables, an exploratory case study is a suitable method [36].

A. Research Setting

1) Background: The purpose of the course given on design thinking, taught by one of the authors of this paper, is to engage students in multidisciplinary collaboration to tackle real-world problems with a human-centered approach. The structure of the course is similar to the framework of design thinking proposed by the d.school at Stanford University [37], one of the pioneers of design thinking practice. The framework includes the iterative process comprising five components/phases of design thinking: empathize, define, ideate, prototype, and test.

Students enrolled in the course were 14 graduate students. The disciplines students represented are mechanical engineering, environmental science and engineering, microengineering, life sciences, data science, management technology and entrepreneurship, and digital humanities.

Students applied the design thinking approach in addressing two projects: A) designing new products and services in light of evolving work and travel conditions in the future (scenarios relevant to 2050) and B) designing new products and services to increase citizen-engagement and co-creation of climate and clean energy strategies on a local level. Project A was a very "quick and dirty" 4-week design thinking project to help students understand the basic methods behind design thinking. Project B, implemented during the 8-week period, allowed students to go through the design thinking steps with plenty of time and intervals between the steps. Guest lecturers such as entrepreneurs and industry experts were invited to participate to add a different perspective and provide knowledge on specific topics/expertise. The student teams documented each class session and consolidated it at the end of each project.

Activities of the course varied as needed from group to group; students were encouraged to use the various techniques that were taught in class inside of their group work and customized to the needs of their problem or challenge as co-designed between the students and their mentor. Student mentors came from industry or the public sector (e.g., in one case the mentor was the mayor of a particular commune/city). Students used a variety of tools and methods during the design thinking process, among them user interviews, stakeholder mapping, persona(s) profile, empathy map, "how-might-we" questions, "point of view" (POV), and rapid prototyping. They were also encouraged to use different materials and mediums, from post-it notes to various types of tangibles. A detailed description of tools and methods used in design thinking process has been discussed elsewhere [6], [9], [13], [38]-[40]. Figure 1 presents major tools and techniques used in the class in connection with different phases of design thinking.

At the end of the process, students were asked to submit an extended logbook of approximately five pages which should include: elaborations on each step of design thinking taken regarding their project – empathize, define, ideate, prototype, test, including pictures, links, etc. Grading was based on project work, and the deliverables for evaluation by the teaching team were: oral presentations provided regularly (at least every two weeks) and logbooks delivered at the end of the projects on the design thinking steps undertaken by the relevant group throughout the two project periods (4 weeks and 8 weeks).

2) Tangible Activities: There were three different applications of tangibles in the semester studied by this research project (fall of 2022). Tangibles were used once in the stakeholder mapping and ideation process for Project A (these two steps were held one after the other in one session). Then, tangibles were used again in Project B for developing the POV, which is a critical step in any design thinking work to focus the ideation stage. Reflecting on the stages of design thinking where the tangibles were used, stakeholder mapping and POV are among the tools and techniques during need finding and problem definition (first stage), which can be deconstructed to “empathize” and “define”, where students need to imagine/learn about users and engage with them, build on things they learned, empathizing, to develop a meaningful challenge, and redefine the problem statement [36] (see Figure 1). In this process, stakeholder mapping is used to identify different stakeholders involved, understand their relationships within broader systems, and facilitate conversation about different roles and power relations [41], [42]. Moreover, POV is a check-point for students to reflect on insights gained from empathizing with users to reformulate and reframe the original problem and present it in terms of an actionable problem statement [5], [37], [40]. And during ideation, a team-based brainstorming process is often employed for proposing and discussing different concepts/ideas. A picture of a model built by a group of students is presented in Appendix A.

For Project A, during stakeholder mapping, students were asked to represent the main parts of their systems on paper with markers and then build on top of the diagram with the visual representations using LEGOs. Students were encouraged to note and discuss potential system issues, whether those pieces of the wider system are important to deal with the systemic problem at hand, and whether they need to change their problem statement. For ideation, students were first asked to discuss what they learned from the interviews, empathy mapping, and stakeholder mapping exercises. Then, each student ideated alone with tangibles and shared their ideas. Teams were then asked to categorize and organize the ideas using whiteboards and start discussions on criteria they wanted to rely on to evaluate the ideas. For the POV activity during the second project, the two-step process of construction and co-construction was implemented:

1) Each student was asked to build a model representing the problem (using their current persona(s)) and think about the story they will tell. They told a story pointing out different elements of the model, and other members listened and provided feedback.

2) Students in each team created a team representation of a POV and discussed their narrative/story.

B. Data Collection

The primary sources of information included observation, surveys, and focus group interviews. Two of the authors observed and took notes during tangible activities. We employed semi-structured observation [43], incorporating an observation protocol with five major categories: engagement, communication, strategies arriving at consensus (if applicable), collaboration, and time spent on different activities. The role of observers was explained to the students, and their participation was only peripheral. The surveys were administered at two points of the semester, one after tangible activities for Project A, stakeholder mapping and ideation, and the other after the POV activity for Project B. Survey questions included: Likert scale items about each activity (e.g., “You enjoyed doing the activity”); open-ended questions about the benefits and challenges of using tangibles (e.g., “Overall, how would you describe the major benefits of using tangibles during the activities?”); and questions about students’ academic and demographic information. The number of respondents for each survey was eight.

The focus group sessions, as primary means of data collection, provided an opportunity to examine diversity of perspectives and emerging patterns and the degree of consensus about using tangibles among participants [44]. Sample questions included:

- Reflecting on your experience, do you remember anything specific about using tangibles? Is there anything that comes to your mind?
- How would you describe your feeling during the tangible activities?

Three focus groups were conducted to gather student's reactions to the interventions, particularly the use of tangibles. A total of nine students participated, four, two, and three, in the first, second, and third session, respectively. Although the initial plan was to have one focus group, we accommodated students’ schedule considering pragmatic issues at the end of semester. The sessions took between 29 to 43 minutes. One of the authors conducted and transcribed the focus groups. Reflecting on some potential ethical concerns, it should be noted that (i) one of the researchers was responsible for sending the recruitment email and subsequent communications, (ii) there were no impacts on students’ grades, and (iii) the teacher did not have access to identifiable data.

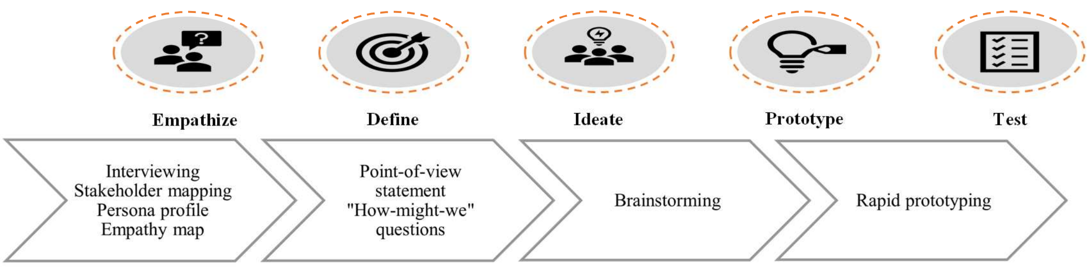


Fig. 1. Tools and methods used in the design thinking course concerning different phases of design thinking process

C. *Data Analysis*

The process of data analysis was informed by the overall purpose of the research, which was to explore the influence of tangibles on design thinking skills. The process began with coding and categorizing field notes and focus group transcripts, transcribed by one of the authors of this paper. In coding focus group interviews, patterns among various groups were identified, noting relevant ideas repeated by several participants [45]. Considering the important contextual elements, for instance, team dynamics and task requirements, we also noted a diversity of opinions highlighting relevant factors. We first used In Vivo Coding as the primary method for coding, in which ideas are represented by words/phrases used by participants [46]. We noted the number of a given code, whether individual participants mentioned a particular topic or idea, and whether a code was mentioned in a particular focus group [47]. After the initial round of coding of all three focus groups, the results were reviewed, factors mentioned most often were identified, and several codes were disregarded. Throughout the process, similar meanings conveyed by different words/phrases by participants were noted [45]. Two authors worked independently on coding the focus group data; disagreements were discussed, and the results were shared with other authors for review and feedback. Qualitative findings were further supplemented by survey data. Table 1 summarizes the major categories and themes found in this study.

IV. Results

The main findings of this study, primarily from focus group and observation data, are organized into four major themes: Engagement, Visualization, Experimentation, and Collective Understanding. It is worth mentioning that survey data showed that most respondents either strongly agree or agree about engagement, communication, and interaction with teammates when they were asked about their experience during different tangible activities (See Appendix B).

A. *Engagement*

All participants discussed different elements of engagement referring to the use of tangibles. In fact, it appears that engagement is the very nature of working with manipulatives.

Although it may not directly explain a particular set of skills, it highlights foundation the for what later in the process emerges: Experimentation and Collective Understanding. Under the major theme of Engagement, students highlighted motivational and affective components. Concerning motivational factors associated with engagement, for instance, some students found themselves immersed in the activities. We considered this separately from the general report of feeling enjoyment. One student said: “After a certain amount of time we were just like small kids building LEGOs, that was quite fun.” Interactivity was another major category highlighted by some participants that illustrated how working with tangibles kept them engaged in the process. For instance, one of the participants pointed out, “[I]t’s interactive they can point to something. Ask a question or move, or ask you to move something to see how it looks here.” It is worth noting that Students’ behavioral engagement was also a prevalent pattern noted through the observation.

B. *Visulization*

Eight out of nine participants discussed the visualization benefit of using tangibles (most frequent ideas coded). Students noted that LEGOs facilitated representing what they have in their minds (Representing Thoughts) as well as sharing and understanding each other’s perspectives (Communicating Ideas). Similar to the last theme, visual referencing is the core of working with manipulatives that facilitate further development in individual and group material and verbal practices. Reflecting on the use of tangibles, one student said: “At that stage for the second project, so last time we had LEGO…we had just an idea and it was really interesting to see how this idea was materializing for each people because we had the same sentence describing the idea but actually seeing what all were thinking about the idea was really interesting because actually I understood that we weren’t really agreeing on the same thing.” A student from a different focus group mentioned: “[S]ometimes maybe you have an idea but you cannot like quite communicate it to your team members or it’s maybe hard to understand but then when you work with LEGO or some other tangibles maybe you can simplify it and it makes your team members maybe understand it.” For observers, examining students’ interactions with peers and tasks, we could interpret that students could quickly capture what they think, represent, and communicate it using LEGO bricks.

TABLE I. Major Themes and Categories (Participant ID in parentheses, FGB2 represents second participant in second group)

Themes	Categories	Sample Quotes
Engagement	Enjoyment	It was quite fun, I had positive feeling. (FGB2)
	Interactivity	It’s interactive they can point to something, ask question or move, or ask you to move something to see how it looks here. (FGC2)
	Immersion	After certain amount of time we were just like small kids building LEGOs, that was quite fun laugh. (FGC3)
Visualization	Representing Thoughts	To be able to present an idea in a simple way and quite fast because you can build it physically and then it’s easier to communicate your idea if you can show physical model that is similar to your model that you have in your head for example. (FGC2)
	Communicating Ideas	You have this thing visible so it’s easy to criticize and to maybe say okay that’s how you see the problem, (FGA2)
Experimentation	Flexibility in Making Changes	You can merge these two solutions or three whatever, quite easily and build one solution because they’re bricks and you can just take them away or add a brick and you can combine these (FGC3)
	Unconventional Atmosphere	I have trouble to start from really raw idea, I need to have all the details fixed, but here I had a different approach, more, okay, I grab something I put it there I see if something else is coming, yeh a bit this freedom, freedom in a sense of not really pressure to have a good idea or really Well thought well rounded from the start. (FGB1)
Collective Understanding	Developing New Understanding	We all had some different imagination of where the problem is and we all built something different and by using LEGO we could just merge it as one overall problem and see our three prior understandings of the problem has these sub-sets of the problem which we can tackle. (FGC1)
	Creating Consensus	Somebody start to put some stuff in this big place at the certain point.. oh okay it is [], this big thing is to represent the difficulty of the people in the campus to meet people in [], so but first that was just a big place which was mean distance also physical. Maybe but also physical representation, but here by somebody start[ing] to put some stuff and somebody else said okay… It could be []. (FGB2)

C. Experimentation

Experimentation captures the benefits of tangibles in creating an environment where different degrees of adaptability may apply and participants are able to make changes to their representations and meanwhile link different ideas. Seven out of nine participants discussed relevant ideas, from flexibility in developing and merging ideas to relative freedom. For instance, one student said: "I think the tangibles can help; it changes the atmosphere of the project and the group work, I feel if you work on something…and you think a lot and it's kind of a break in this like hard process, I don't really know how to describe it.. and it's a bit the atmosphere, more loose I think, and I think this helps to get all the ideas and the spirit is more innovative as well." Another student pointed out the relative freedom in exploring different options: "It is my experience but when I want to create an idea or something I want to make it good from the start, already well done. I have trouble to start from a really raw idea, I need to have all the details fixed, but here I had a different approach, more, okay, I grab something I put it there I see if something else is coming, yes a bit this freedom, freedom in a sense of not really pressure to have a good idea or really well thought, well rounded from the start." At a more collective level, students' comments captured how they could link different perspectives. For instance, one student pointed out how LEGO facilitated mixing ideas, "If it is only in brain it is hard to say "okay we keep this, we keep this, and we mix it," but here we could really mix it together because there is just like bridges and stuff like that, yes for the mixing part it was interesting as well." As evident here and noted earlier, visualization serves as a foundation for the overall influence of tangibles.

D. Collective Understanding

Six out of nine students discussed how tangibles helped team members to develop a new shared understanding of the problem space. The dialogue below between two participants points out how the idea of "growing something together" can emerge through visualizations and interactions with tangibles:

> Participant 1: The fact that when somebody [makes] their model, okay before we talked about ideas, everybody has his own view about an idea, and when you put it into place with LEGOs, it shows, I think, how different perception changes, how the ideas change with the perception of others and extend, A bit about the scope of this idea, I don't know if it's clear. Yeh, like if you have an idea, written words, everybody, let's say, has its own perception of this idea, and the fact that everybody put it in a different form, physical form, let's say with the LEGO, you get the sense that how the others perceive this idea and maybe it gives you another perspective, to yourself, another perspective about idea that you didn't really think about, a new point of view, or new ways of think about it, even though at first everybody thought about the same thing.
>
> Participant 2: Yes, yes, it helps us to agree.
>
> Participant 1: To have a common…
>
> Participant 2. But maybe also expand a certain idea, maybe when you're building it and then your teammate, he thinks, "yes I could have maybe this and this," and then you grow out of like your maybe individual idea, you grow something together.

A few students highlighted that the process of working with tangibles eventually leads to agreement about the meaning that has been co-constructed by the members of the group. See, for instance, the sample quote under Collective Understanding in Table 1. The two constituents of Collective Understanding illustrated by the participants, Developing New Understanding and Creating Consensus, appear to be closely connected with each other.

V. Discussion

Reflecting on the major themes, the use of LEGO bricks can help students to notice the complexity in problem space, surface differences in viewpoints, and ease the process of linking and combing the ideas. The results further confirm the benefits of making ideas tangible as an essential constituent, meanwhile a primary tool, of design thinking process [5], [9], [13], [28]. However, in contrast with prior literature that often focused on the use of tangibles for prototyping and illustrating constituents and functional elements of a given idea or concept, this study demonstrated the influence of tangibles with low perceptual richness during the earlier phases of design thinking. Considering the benefits of materializing and visualizing ideas and the influence on students' affective and behavioral engagement, tangibles seem to play a major role in facilitating playful and interactive experience for the participants. In response to the research question on how tangibles influence design thinking skills, the short answer is by creating an engaging and experiential environment where participants can move towards developing collective understanding, confirming theoretical accounts and the evidence that material practices contribute to constructing new understandings [28]. Specifically, considering design thinking characteristics proposed by Brown [4], we report the impact of using tangibles on collaboration and experimentalism.

An important finding of this study is the potential benefits of tangibles in developing collective understanding, an important cognitive element of collaboration that may have an influence throughout the design thinking process. The construct of shared mental models has often been used in the literature to address the mental representation of knowledge that creates a similar or overlapping interpretation of tasks and working relationships [48], [49]. In practice, efforts that help in arriving at an agreement within groups, such as modifying ideas or co-construction of meanings [49], help promote collective ownership. In other words, team members may feel a sense of ownership for ideas or solutions developed through collaboration [50]. As such, it influences democratic team processes.

While students primarily highlighted the exploratory and playful nature of experiencing constructing and reconstructing ideas, future research shall explore in detail the nature of such experimentation, whether manipulating tangibles can be an explanation for experiencing what Schön [3], [51] calls reflection-in-action, where experimenting is at once exploratory, move-testing, and hypothesis testing [51].

Now, it is critical to have a more systemic view on the overall process, highlight critical differences in perspectives, and reflect on some contextual elements. The process of using tangibles in different activities in the design thinking course can be explained using a time scale from the individual phase to the group phase. Some categories, such as Capturing Thoughts, primarily highlight the individual phase while others, for instance, Developing New Understanding, primarily address the group phase. Nevertheless, the two phases are intertwined, and there can be continuous interactions between the two. Visualization and Engagement are essential parts of the whole process. The benefits of tangibles are meaningful, first and foremost, when they play a role as a visual reference and help along with conversational practices to change and link ideas and develop collective understanding. And for a learning activity with tangible to be effective, engagement appears to play a major role. It is the driving force for experimentation and not being afraid of failure. In general, playful approaches have the potential to be used for teaching and learning transversal skills [52].

There are important contextual elements that we shall reflect on to provide a more holistic picture of what we just illustrated. First, members of one of the focus groups perceived that stakeholder mapping and ideation were not as effective as POV because they were not "relaxed" due to time pressure for preparing the deliverables for the next meeting. It is reasonable to speculate that for students to be engaged in similar playful activities for honing skills, they need to be in a relaxed state of mind, considering the importance of engagement and the very nature of playfulness.

Second, we used LEGOs for two different projects and three different activities. While separating each in connection with the influence of tangibles is challenging, considering the limited evidence collected, we can report that students, in general, found more benefits in POV during the second project. The result is important considering that among the two projects, reflecting on students' work, Project B was more abstract than Project A. It appears that stakeholder mapping did not add much value beyond visualization based on what students reported. For ideation, while ideally it can help to support the individual-group process mentioned above, considering the need for diverse and innovative ideas, using LEGOs may damage the efficiency of the activity; from a more practical standpoint, there might be less benefit, compared to using artifacts with higher fidelity, considering the need for trying out the ideas and receiving feedback from users.

We have highlighted the environment and nature of the activity. Third, we need also to pay attention to individual and group factors. Familiarity and prior engagement with tangibles and overall attitude toward playful approaches may influence the impact of similar activities. Moreover, consistent with the very nature of design thinking, this is a collaborative process and team dynamics and interpersonal relationships may play a significant role throughout the process.

To incorporate this brief overall illustration as a speculation of happenings in similar settings, future work should consider more systematic designs examining material and conversational practices. To this end, several limitations in this study need to be acknowledged. First, we were mainly concerned with the process and did not examine students' models. This is particularly noteworthy, considering that a few students pointed out the potential benefits of creativity. Judgment about the influence of tangibles on the quality and novelty of ideas demands documenting evidence of students' models and how they change over time and with interacting and communicating with others. Second, as reported in the previous studies, material practices are not happening in isolation, and the influence is intertwined with conversational practices. Future studies on the influence of tangibles can include analyzing students' conversations more thoroughly.

VI. Conclusion

In this paper, we explored the influence of tangible objects, LEGO bricks, on design thinking skills in the context of a graduate-level design thinking course. The findings demonstrated the benefits of tangibles concerning two traits of design thinking identified by Brown [4]: experimentalism and collaboration. While foundationally, the use of LEGOs increased engagement and helped visualize thoughts and ideas, the flexibility in linking ideas and adopting new patterns helped team members move toward developing collective understanding. Our findings present a promise for the use of tangibles during earlier phases of the design thinking process.

References

[1] D. Dunne and R. Martin, "Design thinking and how it will change management education: An interview and discussion," *Academy of Management Learning & Education*, vol. 5, no. 4, pp. 512-523, 2006.

[2] C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey, L. J. Leifer, "Engineering design thinking, teaching, and learning," *Journal of Engineering Education*, vol. 94, no. 1, pp. 103-120, 2005.

[3] D. A. Schön, *Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions*, Jossey-Bass, 1987.

[4] T. Brown, "Design thinking," *Harvard Business Review*, vol. 86, no. 6, pp. 84-92, 2008.

[5] L. Carlgren, I. Rauth, and M. Elmquist, "Framing design thinking: The concept in idea and enactment," *Creativity and innovation Management*, vol. 25, no. 1, pp. 38-57, 2016.

[6] R. Glen, C. Suciu, C. C. Baughn, and R. Anson, "Teaching design thinking in business schools," *The International Journal of Management Education*, vol. 13, no. 2, pp. 182-192, 2015.

[7] R. Razzouk, and V. Shute, "What is design thinking and why is it important?" *Review of Educational Research*, vol. 82, no. 3, pp. 330-348, 2012.

[8] V. P. Seidel, T. J. Marion, and S. K. Fixson, "Innovating how to learn design thinking, making, and innovation: Incorporating multiple modes in teaching the innovation process," *INFORMS Transactions on Education*, vol. 20, no. 2, pp. 73-84, 2020.

[9] J. Liedtka, "Perspective: Linking design thinking with innovation outcomes through cognitive bias reduction," Journal of product innovation management, vol. 32, no. 6, pp. 925-938, 2015.

[10] S. Panke, "Design thinking in education: Perspectives, opportunities and challenges," *Open Education Studies*, vol. 1, no. 1, pp. 281-306, 2019.

[11] R. Buchanan, "Wicked problems in design thinking," Design Issues, vol. 8, no. 2, pp. 5-21, 1992.

[12] U. Johansson - Sköldberg, J. Woodilla, and M. Çetinkaya, "Design thinking: past, present and possible futures," *Creativity and Innovation Management*, vol. 22, no. 2, pp. 121-146, 2013.

[13] P. Micheli, S. J. Wilner, S. H. Bhatti, M. Mura, and M. B. Beverland, "Doing design thinking: Conceptual review, synthesis, and research agenda," *Journal of Product Innovation Management*, vol. 36, no. 2, 124-148, 2019.

[14] V. P. Seidel, and S. K. Fixson, "Adopting design thinking in novice multidisciplinary teams: The application and limits of design methods and reflexive practices," *Journal of Product Innovation Management*, vol. 30, pp. 19-33, 2013.

[15] K. Dorst, The core of 'design thinking'and its application. *Design Studies*, vol. 32, no. 6, pp. 521-532, 2011.

[16] E. Coleman, T. Shealy, J. Grohs, and A. Godwin, "Design thinking among first - year and senior engineering students: A cross - sectional, national study measuring perceived ability," *Journal of Engineering Education*, vol. 109, no. 1, pp. 72-87, 2020.

[17] J. Blizzard, L. Klotz, G. Potvin, Z. Hazari, J. Cribbs, and A. Godwin, "Using survey questions to identify and learn more about those who exhibit design thinking traits," *Design Studies*, vol. 38, pp. 92-110, 2015.

[18] C. J. Atman, J. R. Chimka, K. M. Bursic, and H. L. Nachtmann, "A comparison of freshman and senior engineering design processes," *Design Studies*, vol. 20, no. 2, pp. 131-152, 1999.

[19] S. R. Daly, S. Yilmaz, J. L. Christian, C. M. Seifert, and R. Gonzalez, "Design heuristics in engineering concept generation," *Journal of Engineering Education*, vol. 101, no. 4, pp. 601-629, 2012.

[20] C. B. Zoltowski, W. C. Oakes, M. E. Cardella, "Students' ways of experiencing human - centered design," *Journal of Engineering Education*, vol. 101, no. 1, pp. 28-59, 2012.

[21] M. Meinel, T. T. Eismann, C. V. Baccarella, S. K. Fixson, and K. I. Voigt, "Does applying design thinking result in better new product concepts than a traditional innovation approach? An experimental comparison study," *European Management Journal*, vol. 38, no. 4, pp. 661-671, 2020.

[22] E. Justo, A. Delgado, C. Llorente - Cejudo, R. Aguilar, J. Cabero - Almenara, "The effectiveness of physical and virtual manipulatives on learning and motivation in structural engineering," *Journal of Engineering Education*, vol. 111, no. 4, pp. 813-851, 2022.

[23] Z. C. Zacharia, and C. P. Constantinou, "Comparing the influence of physical and virtual manipulatives in the context of the Physics by Inquiry curriculum: The case of undergraduate students' conceptual understanding of heat and temperature," *American Journal of Physics*, vol. 76, no. 4, pp. 425-430, 2008.

[24] M. S. Barner, S. Adam Brown, F. Bornasal, and D. Linton, "Tangibility of representations in engineering courses and the workplace. *Journal of Engineering Education*, vol. 111, no. 1, pp. 162-184, 2022.

[25] L. W. Barsalou, "Grounded cognition," *Annual Review of Psychology*, vol. 59, pp. 617-645, 2008.

[26] Johri, A., & Olds, B. M. (2011). Situated engineering learning: Bridging engineering education research and the learning sciences. *Journal of Engineering Education*, *100*(1), 151-185.

[27] M. Wilson, "Six views of embodied cognition," *Psychonomic Bulletin & Review*, vol. *9*, pp. 625-636, 2002.

[28] I. Stigliani, D. Ravasi, "Organizing thoughts and connecting brains: Material practices and the transition from individual to group-level prospective sensemaking," *Academy of Management journal*, vol. 55, no. 5, pp. 1232-1259, 2012.

[29] A. Beltagui, A. Bell, and M. Candi, "A sociomaterial perspective on epistemic objects in design practice, *Design Studies*, vol. 87, 101201, 2023.

[30] C. Ranscombe, K. Bissett-Johnson, D. Mathias, B. Eisenbart, and B. Hicks, "Designing with LEGO: exploring low fidelity visualization as a trigger for student behavior change toward idea fluency," *International Journal of Technology and Design Education*, vol. 30, pp. 367-388, 2020.

[31] D. Bergen, "Play as the learning medium for future scientists, mathematicians, and engineers," *American Journal of Play*, vol. 1, no. 4, pp. 413-428, 2009.

[32] L. Van Leeuwen, and D. Westwood, "Adult play, psychology and design," *Digital Creativity*, vol. 19, no. 3, pp. 153-161, 2008.

[33] M. Van Vleet, and B. C. Feeney, "Play behavior and playfulness in adulthood," *Social and Personality Psychology Compass*, vol. 9, no. 11, pp. 630-643, 2015.

[34] N. Whitton, "Playful learning: tools, techniques, and tactics," *Research in Learning Technology*, vol. 26, 2018.

[35] V. P. Seidel, and S. O'Mahony, "Managing the repertoire: Stories, metaphors, prototypes, and concept coherence in product innovation," *Organization Science*, vol. 25, no. 3, pp. 691-712, 2014.

[36] R. K. Yin, *Case Study Research: Design and Methods*, 6th ed. Thousand Oaks, CA, USA: Sage Publications, 2018.

[37] Stanford d.school. "bootcamp bootleg." Accessed from: https://dschool.stanford.edu/resources/design-thinking-bootleg, 2018.

[38] W. Brenner, F. Uebernickel, and T. Abrell, "Design thinking as mindset, process, and toolbox: Experiences from research and teaching at the University of St. Gallen," in *Design Thinking for Innovation: Research and Practice*, pp. 3-21, 2016.

[39] IDEO, "The field guid to human-cantered design." Accessed from: https://www.designkit.org/resources/1.html , 2015.

[40] T. Schumacher and S. Mayer, "Preparing managers for turbulent contexts: Teaching the principles of design thinking," *Journal of Management Education*, vol. 42, no. 4, pp. 496-523, 2018.

[41] F. B. Giordano, N. Morelli, A. De Götzen, and J. Hunziker, "The stakeholder map: A conversation tool for designing people-led public services," Service Design and Innovation Conference, 2018.

[42] S. Kernbach, and A. S. Nabergoj "Visual design thinking: Understanding the role of knowledge visualization in the design thinking process," 22nd International Conference Information Visualisation (IV) (pp. 362-367). IEEE, 2018.

[43] M. Q. Patton, *Qualitative Evaluation and Research Methods*. SAGE Publications, 1990.

[44] A. J. Onwuegbuzie, W. B. Dickinson, N. L. Leech, and A. G. Zoran, "A qualitative framework for collecting and analyzing data in focus group research," *International journal of qualitative methods*, vol. 8, no. 3, pp. 1-21, 2009.

[45] R. A. Krueger, Analyzing and Reporting Focus Group Results (Vol. 6). Sage publications, 1997.

[46] J. Saldaña, The Coding Manual for Qualitative Researchers. SAGE Publications, 2021.

[47] D. L. Morgan, Focus Groups as Qualitative Research, SAGE Publications, 1997.

[48] S. Mohammed, and B. C. Dumville, "Team mental models in a team knowledge framework: Expanding theory and measurement across disciplinary boundaries," *Journal of Organizational Behavior*, vol. 22, no. 2, pp. 89-106, 2001.

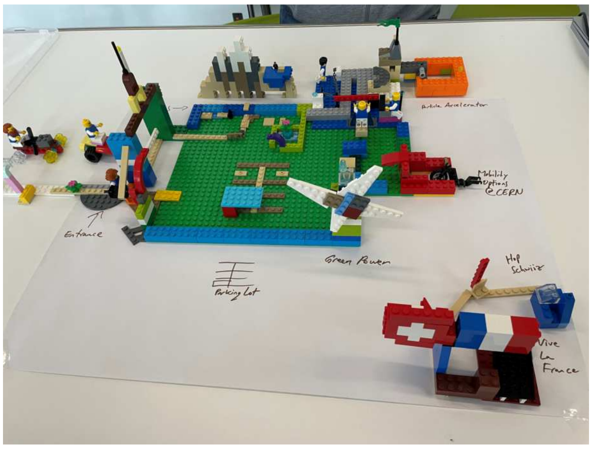
[49] P. Van den Bossche, W. Gijselaers, M. Segers, G. Woltjer, and P. Kirschner, "Team learning: building shared mental models," *Instructional Science*, vol. 39, pp. 283-301, 2011.

[50] S. M. Gray, A. P. Knight, and M. Baer, "On the emergence of collective psychological ownership in new creative teams," *Organization Science*, vol. 31, no. 1, pp. 141-164, 2020.

[51] D. A. Schön, *The Reflective Practitioner: How Professionals Think in Action*, Routledge, 1991.

[52] S. R. Isaac, Y. Jalali, N. Petringa, R. Tormey, J. Dehler Zufferey, "*Are engineering teachers ready to leverage the power of play to teach transversal skills?*" 51st Annual Conference of the European Society for Engineering Education (SEFI), Dublin, Ireland, September 11-14, 2023.

APPENDIX A. *A picture of students' work during one of the tangible activities after combining individual models; note how LEGOs were used as tangibles with low perceptual richness, and complexities in guessing what some pieces represent*



APPENDIX B. *Students' evaluation of tangible activities; stakeholder mapping and ideation (Project A, n = 8) and POV (Project B, n=8)*