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Flare-fork collaborative strategy: expanding design space via opportunistic ideation in engineering product design

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Abstract

Restricted exploration of design space is a problem that novice designers face when solving engineering product design problems. Consequences of limited exploration can be the generation of sub-optimal solutions and fixation towards the first solution idea or known solution space. Expert designers sift through their vast repertoire of solution alternatives and choose the appropriate solution for the given design problem. Novices, however, lack this vast repository of alternative solution approaches. Therefore, it is good practice for novices to expand the problem and solution space and explore different aspects of the product design problem before identifying solutions appropriate for the design problem.

Flare-fork collaborative strategy is a design exploration strategy that enables designers to generate opportunistic ideas related to the design problem and integrate them during the design process thereby expanding problem and solution space. The flare-fork collaborative strategy leverages rapid ideation, and semantic analogy thought transformation strategy to generate new ideas, interlinking ideas in design space map (DSM) for the elaboration of ideas, and thought transformer strategy to manipulate ideas for expanding problem and solution space. This paper describes a study to examine how the operationalization of the flare aspect of flare-fork collaborative strategy as an intervention supports the design process of three teams of students. We found that students frequently traverse between problem and solution space via an intermediate bridge space. Also, regardless of where the students begin, they do a comprehensive exploration of problem and solution space while using flare-fork collaborative strategy. Students' perception of using flare-fork collaborative strategy to explore engineering product design is predominantly positive, with students identifying several ways in which flare aspect of flare-fork collaborative strategy aided them in their expansion of problem and solution space.

Keywords: Engineering product design, Expansion of problem and solution space, Opportunistic idea generation

Introduction

Engineering design is ill-structured (Simon, 1973), necessitating extensive exploration of the design problem. The exploratory nature of the design lends emergent characteristics to the design such that aspects of the problem lead to solution, and solution refocuses the problem (Maher et al., 1996). This iteration between problem exploration and idea generation leads to co-evolution of problem and solution space (Dorst & Cross, 2001; Maher et al., 1996), resulting in an expanded problem and solution space (Hay et al., 2017). The engineering design process can be systematic (Ball et al., 1997), opportunistic (Guindon, 1990), or a combination of hierarchical and opportunistic (Davies, 1991).

The unstructured nature of engineering product design poses a challenge to novice design students. Design activities such as framing problem, identifying goals, constraints, requirements, making decisions, considering alternatives and switching between different modes of thinking, visualizing and gathering information (Atman et al., 2007) makes the design task difficult for novices. Further imposing structured processes during design can create tension among novice designers when they try to include intuitive opportunistic ideas. Consequently, students try to take the path of least resistance and fixate on the first potential solution without exploring alternatives by expanding problem and solution space (Atman et al., 2007). This restricted exploration of design space often leads to fixation (Crilly & Cardoso, 2017) and sub-optimal solutions that may prove intractable at later design stages.

One way to mitigate the ill effects of premature commitment to a solution is enabling students to expand problem and solution space. Problem space comprises the initial problem state, goals, requirements, constraints, and specifications (Simon, 1973; Wiltschnig et al., 2013). The solution space encompasses potential structural combinations that constitute the design, the possible solutions, features, and behaviours of a range of design solutions (Maher & Tang, 2003), and the means of evaluating if the solution meets the requirements (Wiltschnig et al., 2013). The design space encompasses all the aspects of design including the problem and solution space. During co-evolution, designers iteratively explore the problem requirements and design solutions (Maher et al., 1996).

Fostering students’ ability to expand the problem and solution space can help them find design solutions that are more effective, mature, and of higher quality (Alzayed et al., 2019). Flare-fork collaborative strategy is designed to support and promote problem and solution space expansion and multiple conceptual design generation by novice designers while solving an engineering product design problem. Flare aspect supports unrestricted search of problem and solution space by facilitating students to think divergently with divergent thinking strategies. It combines collaboration, shared visual representation, and strategies to restructure thinking patterns. Students can opportunistically decompose the design problem but still benefit from the subtle structuring introduced by the pedagogy. Fork helps students in identifying interesting perspectives, evaluating and devising conceptual designs for the given design problem.

This paper discusses the collaborative learning environment for the flare aspect of the pedagogy. We use conjecture mapping to understand how activities, artifacts, design processes in a collaborative setting can support the expansion of problem and solution space. This paper tests the theoretical conjecture that informs the flare pedagogy and examines students' experience using the flare-fork collaborative strategy for designing a product. An initial technology based implementation based on students' perceptions on desired modifications is also discussed.

Related work

A literature search revealed different methods by which researchers have envisaged a design support tool for designers. These include computational support that works like recommender system (Verhaegen et al., 2011), tools to support the exploration of problem space (Murray et al., 2019), solution space (Alzayed et al., 2019), idea generation strategies (Studer et al., 2018) and framework for engineering design instruction (Crismond & Adams, 2012).

Computational systems such as 'Product aspects in design by analogy' (PAnDA) (Verhaegen et al., 2011) provide designers with a ready corpus of system functionalities they need to focus on during ideation. Here techniques such as model-based reasoning, design by analogy are used to suggest examples or support designers in knowledge structuring. Such recommender systems are ideal for designers to establish boundaries of design space quickly. However, they do not support novice designers in developing strategies to expand the design space independently.

Design support tools such as 'Problem formulator' (MacLellan et al., 2013) enable designers to structure problem space. The tool uses ontology with entities such as requirements, functions, artifacts, behaviours, and issues to organize the problem space. Perspective-taking using systematic problem exploration patterns is another approach for expanding the problem space. Murray et al. (2019) have identified 27 different problem exploration patterns that can aid engineers in reframing the presented design problems. However, a combination of problem exploration patterns is expected to help designers narrow down the problem space as against expanding the problem space.

Product dissection (Alzayed et al., 2019), as a solution-oriented approach, is an effective method to motivate idea generation among designers. Research indicates that dissection of analogically distant products, either physical or virtual, helps generate more novel ideas and explore large solution space. However, the choice of the product to be dissected can influence design fixation due to particular example exposure (Jansson & Smith, 1991).

Design Teaching and learning matrix (Crismond & Adams, 2012) is a compilation of informed designer approaches for different design goals supported by useful teaching-learning strategies to achieve said goals. The purpose of this matrix is to help teachers and students monitor their evolving design skills, concepts, and dispositions, equip them with design strategies and improve their understanding of engineering design. The design teaching learning matrix is comprehensive but a theoretical contribution.

Comparing design approaches, though not explicitly stated, product dissection and designing from perspectives seem to support opportunistic decomposition and design co-evolution. In contrast, problem formulator approach and recommender systems suggest a structured hierarchical approach. Most of the studies report on the nature or quality of the conceptual design outcomes. They do not comment on the nature of design exploration or the expanded problem and solution space. Design support tools target simplifying specific aspects of design such as idea generation, problem space expansion, solution space expansion, or problem formulation, each of which covers a particular part of the design. There is a need for a system that supports integrating isolated opportunistic ideas at different levels of abstraction into the design problem and solution space. Flare-fork collaborative strategy aims to meet this requirement so that novice designers can generate the problem and solution space spanning different design aspects.

Flare-fork collaborative strategy design

Theoretical basis

Our solution is grounded in the design process of co-evolution and opportunistic decomposition. During co-evolution, the exploration of problem and solution spaces happens iteratively following design actions such as generation, reinterpretation, analysis, evaluation, synthesis, and reformulation (Dorst & Cross, 2001; Hay et al., 2017). Design boundary expansion offers the opportunity to find better designs that have so far been unexplored. Co-evolution can be problem-driven, solution-driven, information-driven, or knowledge-driven (Kruger & Cross, 2006). Co-evolution can result in new requirements, changed design goals, development of partial solutions, and solution insights for emerging requirements of the design problem (Guindon, 1990).

Design decomposition is opportunistic if design aspects are created asynchronously at varying levels of abstraction within the design space (Davies, 1991). Opportunistic decomposition is non-systematic and multidirectional (Visser, 2008) and provides an opportunity to factor in unplanned information constructed or activated during design (Guindon, 1990). Novices require support to integrate opportunistic possibilities into the co-evolution process. Such a design support tool needs to be compatible with the opportunistic nature of design activity rather than imposing a hierarchically structured design process constraining the designers (Visser, 1994).

A key approach recommended to avoid design fixation is forming multiple perspectives (Murray et al., 2019) from diverse interpretations, which is known to be promoted using collaboration. When collaborators grapple with the problem, present alternative perspectives, establish a common frame of reference, negotiate meaning and restructure ideas, they mutually construct knowledge (Cress et al., 2015).

Shared representation facilitates access to parts of knowledge of the collaborating group in distributed resources such as a concept map, sketches, and shared worksheets. Shared representation works as a mediating tool to engage and facilitate cognitive processing. It also supports design reasoning (Petre, 2004), transformation, modification, and reformulation of concepts (Goldschmidt, 1997). Concept maps (CMAP), for instance, helps designers externalize their internal cognitive structure, thereby making individual knowledge more explicit. It presents multiple dimensions of the picture concurrently facilitating creative association between ideas via critical reflection among collaborators (Van Boxtel et al., 2002).

Divergent idea generation requires the designer to uncover new ways of viewing the problem and solution by intuitive associations and systematic variations (Daly et al., 2014). Idea stimulating strategies such as adapting, combining, and rearranging, play an essential role in imagination by making manipulation of information more explicit (Eberle, 1972). Cognitive aspects of creativity (Daly et al., 2014) elaborates on mechanisms and thinking patterns that can support the generation and elaboration of ideas. Such strategies enable designers to span the design space, contemplate employing non-obvious ideas as a solution concept, and de-fixate from tried and tested solution ideas (Daly et al., 2012). Figure 1 summarizes the theoretical basis of flare-fork collaborative strategy.

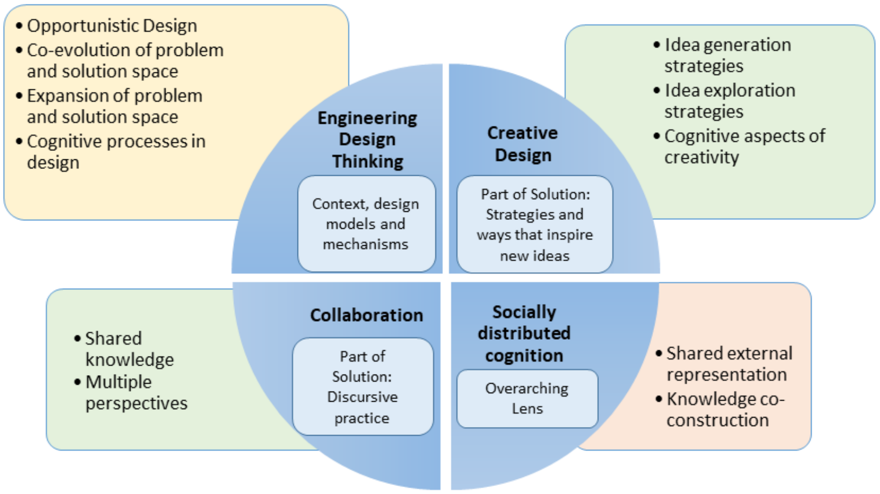


Fig. 1 Theoretical basis for flare-fork collaborative strategy

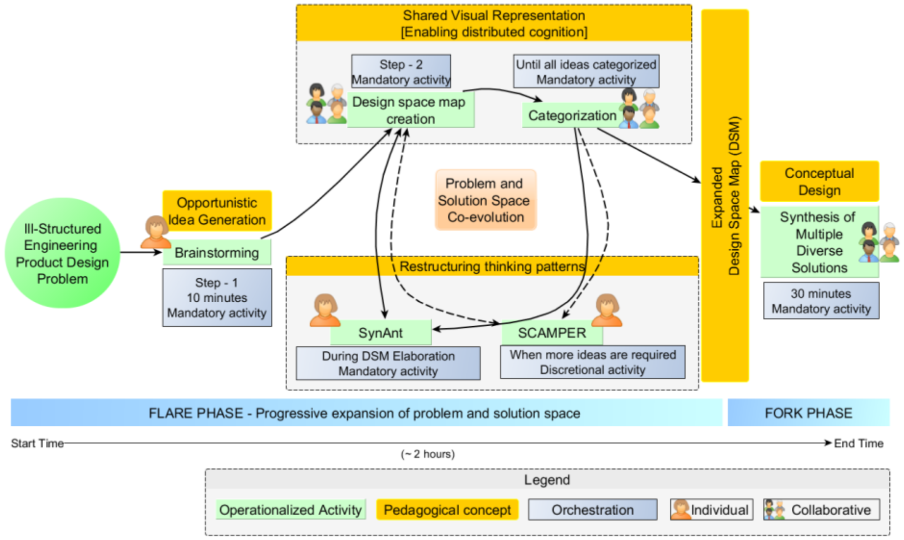


Fig. 2 Flare-fork collaborative strategy

Pedagogical features

Flare-fork collaborative strategy is designed to help novice designers to build on their opportunistic ideas collaboratively. The flare aspect promotes the progressive expansion of problem and solution space. Fork supports the design of multiple conceptual solutions by identifying and designing for different perspectives.

Flare-fork collaborative strategy has both individual and collaborative parts. Individual activities foster each designer's creativity without any external influences or bias. Collaborative activities focus on fleshing out and elaborating on abstract or sketchy design ideas generated individually. Figure 2 illustrates the flare-fork collaborative strategy.

Opportunistic idea generation is supported by successively providing designers with means of identifying new search cues for exploring the design. While *collaboration* helps this by bringing in new perspectives from each participant, thought transformer strategies (SCAMPER and SynAnt) provide students with methods to restructure their thinking patterns and modify existing ideas to get a fresh perspective.

Opportunistic idea generation via brainstorming is a strategy to generate as many opportunistic ideas about the problem statement as possible (Stroebe & Diehl, 1994). An opportunistic idea may be any of the various aspects of the design problem, such as a statement that characterizes the problem, suggests some solution to part of the problem, describes some feature to be included as a part of the solution or highlights some phenomena related to the problem (Baker & van der Hoek, 2010). Scaffolding in the form of idea categories provides anchor points for the designers to direct their thinking. These idea categories synthesized from design literature are common aspects of engineering product design that designers need to consider when designing. They include functionality, shape/structure (Gero & Kannengiesser, 2004), requirements for working, principle of operation, analogy (Lawson & Loke, 1997), questions (Eris, 2003), and sketches (Lawson & Loke, 1997) as a few exemplar idea categories. The scaffolding is optional and can be used by the designers only if they fail to generate any ideas about the design problem.

Thought transformer strategies such as SynAnt and SCAMPER facilitate *restructuring thinking patterns* to generate more opportunistic ideas. SynAnt is a verbal analogy based idea generation activity. Designers are provided with a worksheet with structured tasks to help them identify keywords from the design problem, search for synonyms and antonyms that provide nuanced meaning to the keywords, thereby subtly shifting their way of viewing the design problem (Linsey et al., 2010). This shift in viewing the design problem is explored further as idea sources using external information on World Wide Web. SCAMPER (substitute, combine, adjust, modify, put to other uses, eliminate, reverse/rearrange) is an idea transformation scaffold provided for designers to manipulate existing ideas by changing context or perspective, thereby triggering imaginative exploration of solution space (Eberle, 1972). SCAMPER action verbs with verbal instructions function as a scaffold.

Design space map (DSM) as a *shared visual representation* brings semantically and conceptually diverse aspects of the design in one place and facilitates simultaneous consideration of all design parts (Van Boxtel et al., 2002). It enables the designers to make non-apparent distal connections. It also helps designers uncover missing information and ensure the comprehensiveness of design exploration.

Orchestration via turn-taking ensures participation and contribution from all collaborating designers. Each participant takes turns picking a random idea from the shuffled set of opportunistic ideas and connecting it to build the DSM. The rules of constructing DSM has been kept minimal so as to lower the cognitive threshold as compared to structured decomposition and encourage expansion of design space. Designers actively discuss the idea, thereby bringing out the different features, characteristics, limitations, assumptions, and possibilities making the vague idea more definite. In addition to connecting the ideas generated during the ideation session, these additional aspects of the idea discussed while linking it to the DSM contribute to expanding the problem and solution space. Exemplar links containing relationships such as ‘is-a’, ‘form of’, ‘type of’ scaffold the linking process.

Categorizing the DSM helps designers consolidate their ideas and take stock of the expanded problem and solution space. Categorization is an important cognitive process in design that allows designers to generalize existing experiences and add new experiences to enhance current categories of knowledge (Oxman, 1990). The orchestration instruction ensures participants reach a consensus about the categories in the DSM.

Categorization activity ends the flare aspect of the flare-fork collaborative strategy. The fork part of the pedagogy aims at helping students identify functionalities that their product must possess, achieve these functional requirements, and generate conceptual designs for diverse perspectives.

Conjecture map

Conjecture mapping is a systematic method to clearly state how the salient features of the learning environment are expected to produce the desired outcomes (Sandoval, 2014). We use conjecture mapping to articulate how the different components of the intervention, viz. the activities, artifacts, resources, scaffolds, and the transactions between these components, interact to facilitate problem and solution space expansion. We draw our design and theoretical conjectures from the literature on typical processes that facilitate divergent and convergent thinking to enhance creative exploration of the problem and solution space. Figure 3 depicts the conjecture map for the flare aspect of the flare-fork collaborative strategy. Our design conjectures are:

- Collaboratively creating a DSM with a DSM creation tool supports combining and interlinking far-off ideas.
- Individual ideation with semantic analogy thought transformer strategy supports the generation of new keywords and ideas.
- Transformation and modification of ideas using SCAMPER thought transformer scaffold individually leads to reorganization of ideas by changing context or perspective.

Our previous research (Narayanan & Murthy, 2019) found evidence to support our design conjectures. We found that collaborative DSM as an external representation of the collective ideas of the team mediated linking of ideas within and between different

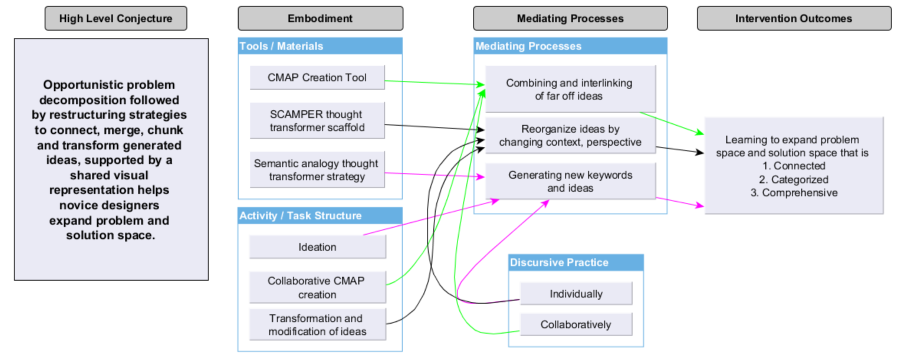


Fig. 3 Conjecture map for flare-fork collaborative strategy

categories identified by the students. We found evidence for semantic analogy thought transformer usage leading to the generation of new keywords and ideas.

Our theoretical conjecture is: Learning to expand problem and solution space will occur when students generate new keywords and ideas, reorganize ideas by changing context or perspective, and combine and interlink far-off ideas.

This paper focuses on how students explore the problem and solution space during design problem solving using the flare-fork collaborative strategy. Essentially, we investigate the role of mediating processes viz. use of new perspectives, new keywords, and linking far-off ideas to expand the problem and solution space.

Research methodology

There are two research questions as the focus of this study:

1. How do students explore problem and solution space during design problem solving using the flare aspect of flare-fork collaborative strategy?
2. What are students' experiences of using the flare aspect of flare-fork collaborative strategy for designing their product?

Participants

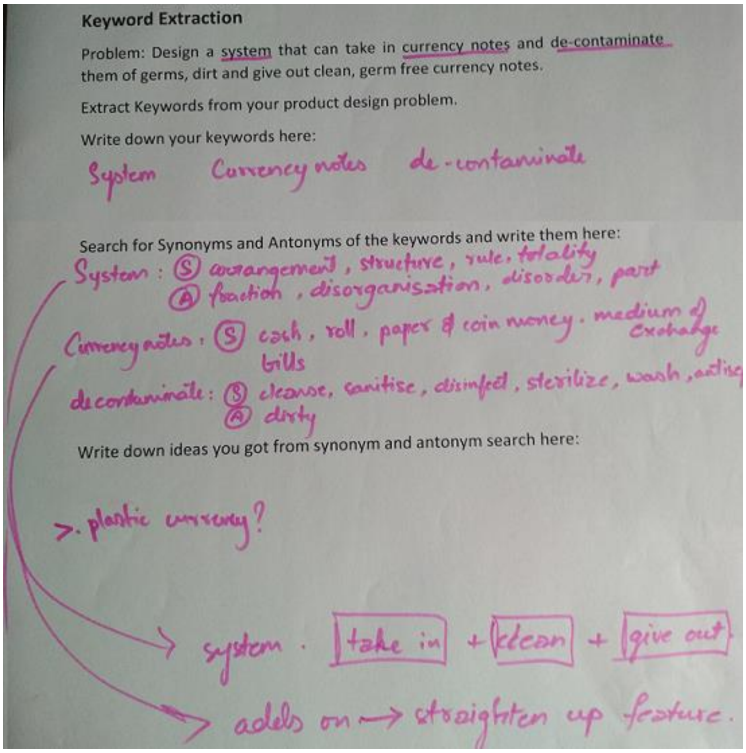
We conducted a study with three groups to study the influence of flare-fork collaborative strategy for engineering product design on a collaborating team. Our target population comprised of students from final year engineering undergraduate degree and first-year postgraduate degree. At this level, students have some experience doing design while working on capstone projects but have not attained expertise in design. We looked for participants from different branches of engineering to bring in diversity in perspectives, diverse information sources, and different methods to solving a design problem (Petre, 2004). We did a purposive sampling and created groups of triads and dyads such that each participant was from a different engineering branch. The students belonged to Computer Science, Chemical, Electronics, Metallurgy, and Industrial design branches. While group 1 and group 3 were composed of three students each, group 2 was composed of two students.

Procedure

We gave the students a design scenario – *'Sushma observed that she falls sick whenever she handles money. She then came across an article that described soiled currency notes as a source of health problems. She has decided to hire your team to develop a 'Currency Cleaner' that makes currency notes safe.'* The students first brainstormed individually for 10 minutes. The facilitator prompted them to use idea categories scaffold as search cues. They used post-it notes to write down the different ideas. On the culmination of the brainstorming session, the facilitator collected the post-it notes from all the students and shuffled them. Students took turns, picked up a random post-it from the shuffled set, and connected it to the evolving DSM after deliberations among themselves. The facilitator prompted the students to elaborate the DSM by adding more ideas, transforming existing ideas, or interlinking the ideas after connecting the initial ideas. Whenever there was a lull in the discussions, the facilitator prompted them to use SCAMPER thought transformation strategy. For the SCAMPER activity, students individually used the action verbs presented on a whiteboard to trigger idea transformation. New ideas thus generated were added to the growing DSM. This activity is however optional.

When students reached saturation in their discussions the facilitator initiated the SynAnt thought transformation strategy. The students followed the steps in the worksheet (Figure 4) and accessed the World Wide Web for a focused search. At the end of the activity, students individually articulated their list of keywords, synonyms, and antonyms, and ideas that these synonyms or antonyms triggered and added them to the DSM.

Once students reached saturation in their exploration of the design problem, they collaboratively categorized the ideas by labelling them to obtain the expanded DSM. The whole session lasted about 2 hours. No strict rule for sequencing of the thought transformation strategy activities and categorization activity was imposed. The students were urged to link and categorize all ideas generated. The orchestration is loosely scripted



Keyword Extraction

Problem: Design a system that can take in currency notes and de-contaminate them of germs, dirt and give out clean, germ free currency notes.

Extract Keywords from your product design problem.

Write down your keywords here:

System Currency notes de-contaminate

Search for Synonyms and Antonyms of the keywords and write them here:

System : Ⓢ arrangement, structure, rule, totality
Ⓐ fraction, disorganisation, disorder, part

Currency notes : Ⓢ cash, roll, paper & coin money. medium of exchange
bills

decontaminate : Ⓢ cleanse, sanitise, disinfect, sterilize, wash, antise
Ⓐ dirty

Write down ideas you got from synonym and antonym search here:

>. plastic currency?

→ system . take in + clean + give out

→ adds on → straighten up feature.

Fig. 4 Sample SynAnt worksheet of a student so as to not disturb the natural problem solving dynamics and avoid inducing linearity that can interfere with the students' cognitive process.

Finally, students collaboratively generated two conceptual designs for the given problem using the expanded DSM as the corpus. Figure 2 illustrates the procedure followed for implementing flare-fork collaborative strategy. The students were then interviewed to elicit their experiences while using the flare-fork collaborative strategy to tackle the design problem.

Data collection

We video-recorded the whole intervention with two video cameras. One recorder captured the wide-angle view of the actions and behaviour of the group, while the other camera was a close-up of the DSM under development. We also audio recorded the whole proceeding. We made regular unstructured observations for recording the activities of the students during the intervention. We used the worksheets and expanded DSM as artifacts for analysis.

We conducted an hour-long interview after the groups completed the conceptual designs of their product using the flare-fork collaborative strategy. The broad themes of the interview were students' experience of using flare-fork collaborative strategy, their perception of specific activities, sequence and orchestration of activities, and representation of generated information. Some sample questions were:

1. What are your thoughts and reflections about your design experience?
2. What were the difficulties you found while following the intervention for design?
3. What are your thoughts on creating the DSM?
4. What are your thoughts on SynAnt activity?
5. Can you think of some example where you could use SCAMPER?

Data analysis

To investigate how students explore the problem and solution space during design problem solving using flare-fork collaborative strategy (theoretical conjecture), we derived a framework from the existing design process and product elements framework (Mehalik & Schunn, 2006) relevant to conceptual design. The design process aspects in the framework are derived from a meta-perspective of elements/stages of documented observable design process elements that represent design activities derived from several separate empirical studies on aspects of 'good design' (Mehalik & Schunn, 2006). The framework followed by Guindon (1990) to study the early stages of the software design process contributes to fine-grain design process aspects in the problem space, viz. exploration of scenarios or use cases. The FPBS framework (Zhang et al., 2012) is a design knowledge representation framework to support the reuse of existing design knowledge and innovation. This framework identifies four design domains - function, working principle, behaviour, and structure. These domains help describe the product in greater detail and can provide valuable insights into students' exploration of the problem and solution space during design. The aspects are classified into problem space (PS), solution space (SS), and intermediate space (IS). Intermediate space contains aspects of the design space that support traversal between problem and solution space. The final derived framework is summarized in Table 1.

Table 1 Design process and product aspects adapted from Guindon (1990), Mehalik and Schunn (2006), and Zhang et al. (2012)

Aspects	Definition	Example
Scenario (PS)	A description of possible actions or events or situations related to the design problem.	Currency exchange in railway station, office, cinema counters
Problem rep (PS)	Framing of a design task including goals, issue, artifact that needs to be analyzed, synthesized, investigated or constructed.	Does external environment affect currency cleaning
Constraint scope (PS)	Constraints limit how a design can fulfil goals within problem frame. Designer needs to explore how constraints are affecting the design.	Assume the dirt on currency is dust
User perspective (PS)	Capturing various aspects of requirements, needs, habits of the users.	The user may be a banker counting a lot of currency
Eval design alt (SS)	Designer's actions to use a framework of performance criteria (goals and constraints) to search and evaluate potential design solutions.	Which one is better - UV or chemical or mechanical cleaning
Func decomp (SS)	Breaking down design into several detailed aspects to investigate how the design performs, interacts and contributes to overall functionality.	Create a note counter that has UV technology
Principle (SS)	Exploring different concepts and principles relevant for realizing the functionality expected of the design.	Use ultraviolet technology to kill germs
Function (SS)	Intended operation or desired purpose of the design.	Clean physical dust particles and sterilize the currency
Structure (SS)	Carrier for function. It comprises definition of objects, their relationships in a physical solution.	Easy to carry equipment, sleek and portable
Behaviour (SS)	Dynamic / Static movement or action of a component that can realize specific function. It describes actions or processes of an object or artifact.	System takes in one note and inside there is an OCR which reads it and stacks it on one side
Engg facts (SS)	Exploring specific knowledge about some property of an aspect of a design. Includes common principles.	Hot water damages security features in currency
Failure analysis (IS)	Gathering knowledge associated with what produces a failure i.e., when design falls short of goals or performance expectations.	Things may stick to plastic also
Redef constraints (IS)	Designer defines a constraint to achieve an original goal.	Actually this can be a problem with food stalls also – like oil spot

We used the transcription of student discussion generated from audio and video recording during the study as data. We chose the unit of analysis to be one conversation turn. However, to establish context, we have referred to sentences immediately before or after the sentence under consideration. We used content analysis (Cohen et al., 2007) to identify and assign codes from our design process and product analytical framework to the utterances made by the students during the intervention. Two raters who have experience in doing qualitative data analysis as well as knowledge of engineering design, performed the coding on a partial dataset. They then discussed and came to a consensus regarding the assigned codes and repeated the process on a different dataset. We calculated the Cohen's Kappa for the coding of utterances to be 62.04%, indicating substantial agreement between the two raters. The researcher then coded the remaining utterances. Additionally, we analyzed students' DSMs to identify student-generated categories and links between and within these categories.

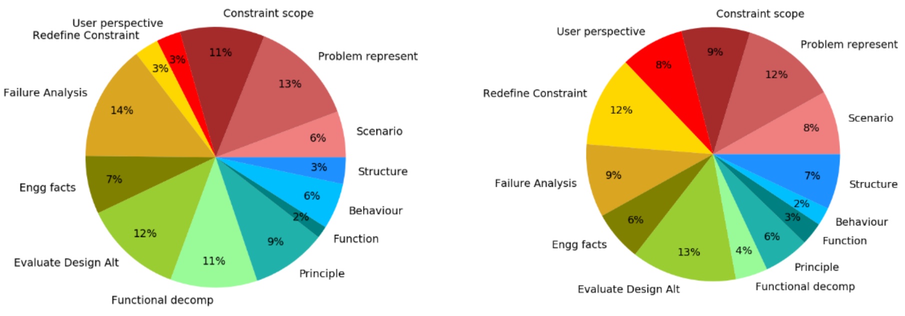
We used the transcribed interviews to investigate students' experience using the flare-fork collaborative strategy for designing their product (RQ2). We did an inductive thematic analysis (Braun & Clarke, 2006) with one conversation turn as the unit of analysis. The broad lens considered was their product design experience. We excluded utterances related to planning, queries regarding intervention, and banter. Two independent coders carried the initial coding on the software Weft QDA. We followed this by a discussion on the initial codes. Subsequently, a thematic map was generated to collate codes into potential themes. We pruned the thematic map based on the research question. Another researcher verified the pruned thematic map.

Findings

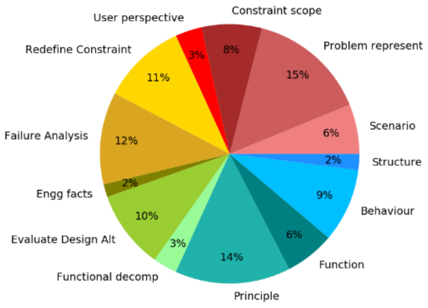
RQ 1: Students' expansion of problem and solution space

Distribution of utterances

The pie charts in Figures 5(a), 5(b), and 5(c) show the percentage utterance of each group for each aspect of the engineering process and product aspects during the intervention. All three groups addressed the different aspects of engineering design spanning problem space, intermediate space, and solution space, albeit to varying degrees. The percentage of utterances of each participant in group 1 is 31.2%, 33%, and 35.8%. In group 2, the percentage of the utterance of the dyad is 48.7% and 51.3%. For the triad in group 3, the percentage of individual utterances are 34.8%, 32.2%, and 32.8%.



(a) Group 1 (b) Group 2



(c) Group 3

Fig. 5 Frequencies of design aspects occurring during design process

Co-evolution of problem and solution space

During the design process, the students frequently traversed between problem space, solution space, and intermediate space. The frequent traversal can be seen in Figure 6, depicting the design progression of group 1 in the three spaces, obtained from the application of codes from Table 1 to the transcribed data. The highlights indicate the different types of traversals viz. between pairs of problem space aspects via intermediate space, pairs of solution space aspects via intermediate space, and between problem and

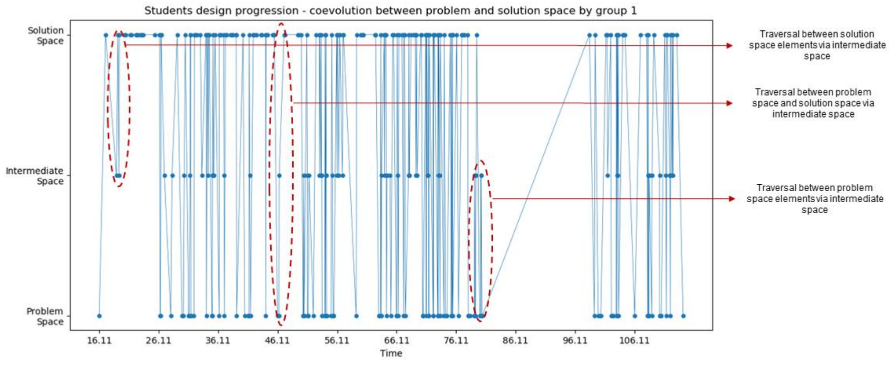


Fig. 6 Traversal between and within different design spaced during design co-evolution

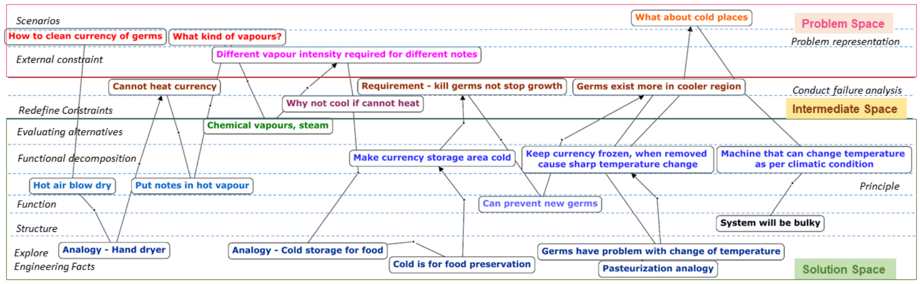


Fig. 7 Scenario from narrative depicting expansion of problem and solution space

solution space via intermediate space. Such traversals indicate the co-evolutionary nature of the design process by interleaving the problem and solution domain via intermediate space.

Figure 7 is constructed from a 10-minute episode during the design progression of group 1. We can see that students moved from problem space *(how to clean germs from currency)* to different levels of abstraction in solution space *(including principles to use such as hot air blow dry, functional decomposition such as a system facilitating change in temperature, engineering facts such as cold being for food preservation)*. They followed it with some failure analysis on the proposed solution *(currency cannot be heated)*. They then identified new constraints *(using cooling instead of heating)* and requirements and a new problem *(different vapor intensity required for a different currency, considering local climate)*. This episode shows that students expanded problem and solution space by frequently traversing across different spaces and traversing through different levels of abstraction within the spaces during the design process.

Delving deeper into the nature of co-evolution of group 1, as seen in Figure 8, group 1 spent a significant amount of time in solution space during the DSM creation section. While

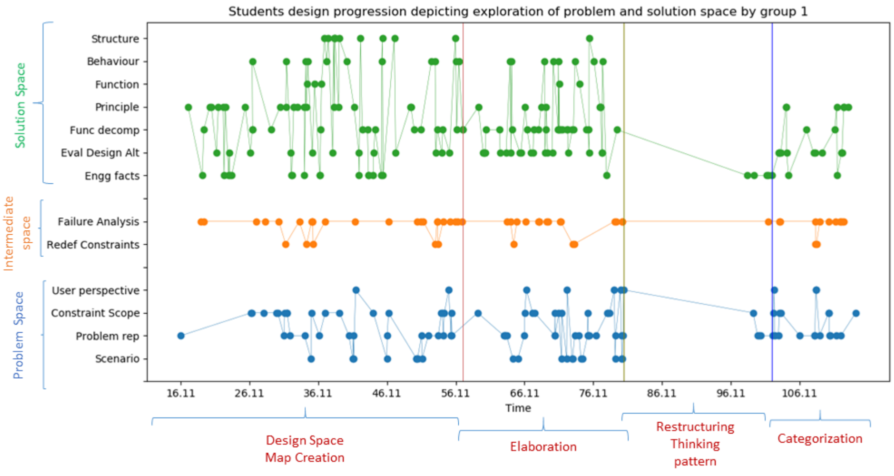


Fig. 8 Detailed design progression by Group 1

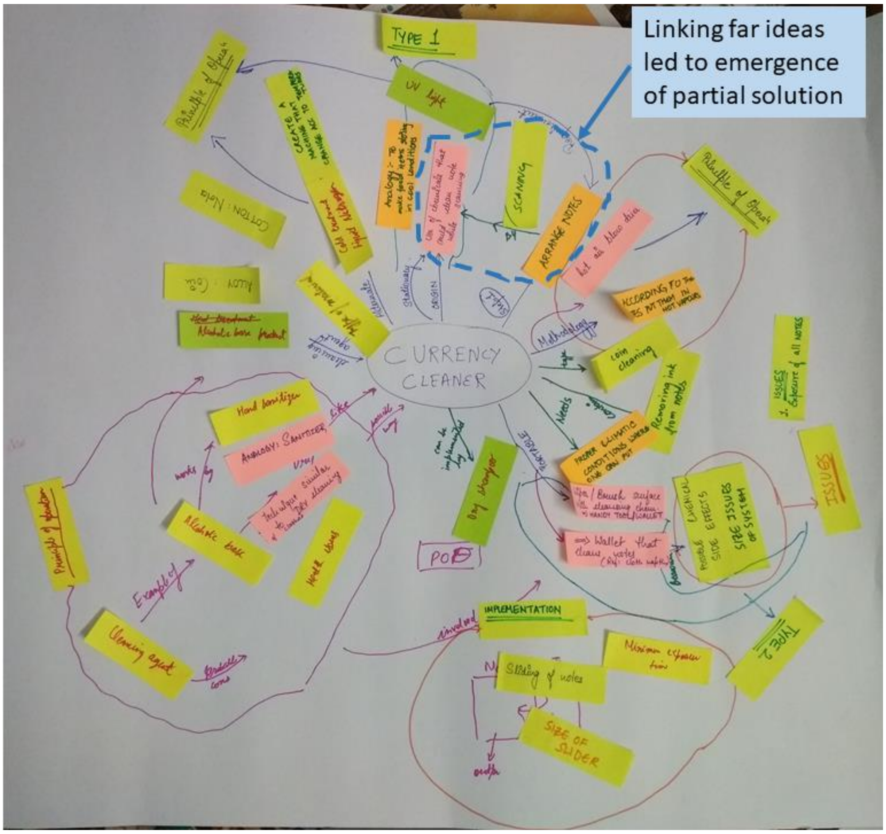
they considered principle during the initial part of the DSM creation, they focused on behaviour expected of the system and structure during the later part. The students came up with several principles of cleaning and killing germs *(alcohol-based cleaner, UV light)* and product description *(brush surface with cleaning chemical as a handy tool, wallet that cleans notes)* as partial solutions. They used analogies *(like technology for dry-cleaning, like food items stored in cold conditions)* for inspiration. When connecting these ideas to form the initial DSM, the students focused more on problem representation and constraint scope in the problem space. Some of the problem perspectives they looked into were, *'what are the non-water based cleaning methods?', 'how to scale a given cleaning process?'* Failure analysis *(miniaturization of process of dipping currency in alcohol is not feasible, hand sanitizer is not the same as currency sanitizer)* and redefinition of constraints *(consider drastic temperature difference to kill germs of any type, hot chemical vapors can be used without damaging currency)* supported exploration of the problem perspectives.

The traversals were mainly driven by problem representation and constraints in the problem space and the solution space by evaluating design alternatives, engineering facts, and functional decomposition. Failure analysis in the intermediate space facilitated traversal between spaces. During the elaboration section, solution space activity was dominated by functional decomposition and evaluating design alternatives. Scenarios were considered in the problem space to facilitate the elaboration.

In the third section, where the students restructured their thinking patterns using SynAnt, the ideas were chiefly about problem representation and constraint scope. Some of the new ideas generated post SynAnt were: *material of currency (paper, cotton, plastic), methods to decontaminate such as fumigate, lustrate*.

Students evaluated design alternatives in the final section of categorization by using engineering facts and principles in the solution space. They also considered problem representation and constraint scope in problem space. Overall, group 1 displayed a solution-driven co-evolution process. Figure 9 shows the expanded problem and solution space of group 1. We can see the emergence of partial solutions by linking far-off ideas. For example, *'arranging notes'* linked to *'using chemicals to clear notes'* and *'by scanning'* led to the emergence of a sequence of the currency cleaning process.

Group 2 students emphasized the problem space during DSM creation and elaboration sections. Their initial ideas included principles of cleaning and killing germs *(equipment with brush, chemicals to kill germs)*, alternative to cleaning currency *(using gloves, hand sanitizer)*, alternative to using currency *(e-currency)*, understanding stakeholders *(what is the client's job, how frequently does she have to handle currency)* and final product design description *(easy to carry equipment, note counter with UV technology)*. While using these preliminary ideas to create the initial DSM, the students devoted considerable efforts to

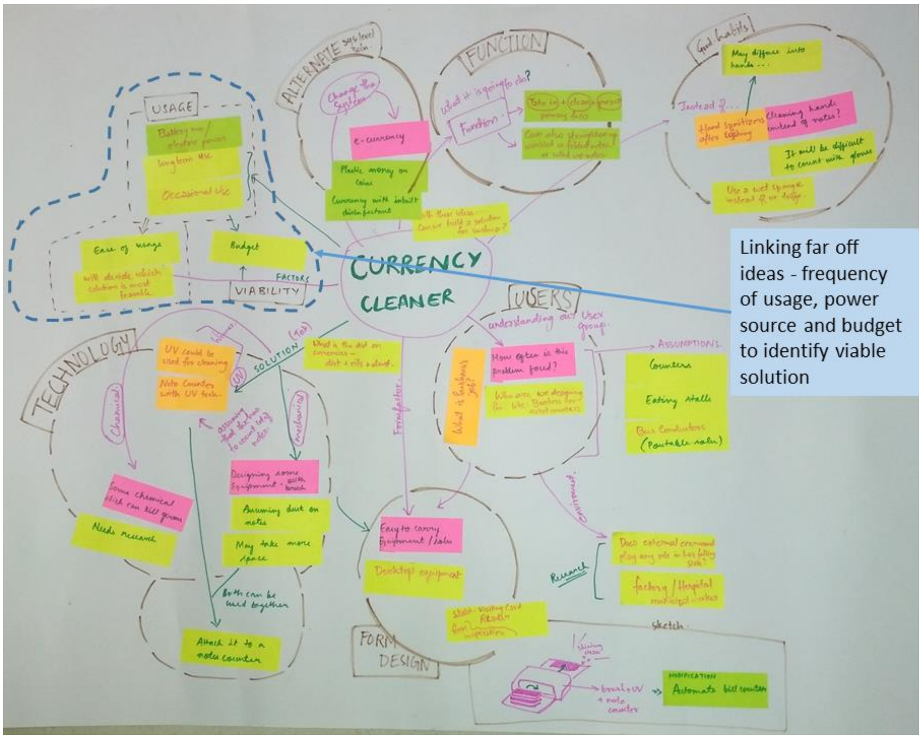


Linking far ideas led to emergence of partial solution

Fig. 9 Expanded problem and solution space of Group 1

understand the problem from user perspectives. For this, they imagined real-life scenarios to get new perspectives on the problem. Some of the perspectives they used to explore the problem space were, *'who are the stakeholders?', 'what are the places where currency transactions occur?'* They bridged their traversal back and forth between problem and solution space by failure analysis such as *'economic viability of currency cleaner', 'wearing gloves may hinder regular activities.'* During the latter part of the elaboration section, the focus shifted to solution space, where they discussed different aspects of the solution such as functionality, structure, and functional decomposition. Subsequently, they generated new ideas using SynAnt, such as *'plastic notes', 'a feature in the system to deal with deformed, crumpled currency'*. Overall, group 2 displayed a problem-driven co-evolution process. Figure 10 depicts the expanded problem and solution space created by group 2. The highlighted portion shows an example of how participants linked far-off ideas to generate a partial solution.

Group 3 spent a significant amount of time on solution space during the DSM creation section. Their initial ideas covered a range of aspects of design problem such as the principle of cleaning and killing germs *(UV radiation, high-frequency cleaning)*, final product design description *(wallet)*, alternatives to cleaning currency *(gloves, sanitizers)*,



Linking far off ideas - frequency of usage, power source and budget to identify viable solution

Fig. 10 Expanded problem and solution space of Group 2

alternatives to using currency *(cashless transaction)*, and identifying problem source *(kind of germs, sources of contamination)*. While linking these preliminary ideas, the students extended them by bringing in new perspectives of viewing the problem and identifying possible solutions. For example, when linking the idea of using *'high-frequency vibration for clearing dirt,'* one of the students raised the question of *'means of identifying if the currency note has been cleaned.'* This new requirement in problem space led to a new idea of a *'marker for cleaned notes'* in the solution space. Some of the other problems explored were *'sources of contamination,' 'different levels of contamination.'* Students also explored far-reaching ideas such as *'scaling the system and bearing the expense of cleaning currency.'* While exploring solutions for the above interpretations of the problem, the exploration between problems and solutions were bridged by failure analysis *(heating currency can deform it, some materials cannot sustain water exposure)* and redefined constraints *(make banks responsible for cleaning currency)*.

Students used SynAnt extensively, covering principle, behaviour, and evaluating design alternatives in the restructuring thinking pattern section. The new ideas generated post SynAnt strategy were: *'bleaching and reprinting currency,' 'coating currency with a varnish or laminate-like layer to prevent the currency from getting soiled.'* In the categorization section, students looked mainly at functions and principles. Overall, group 3 displayed a solution-driven co-evolution process. Figure 11 depicts the expanded

Linking far off ideas – cleaning mechanisms, detection mechanisms to generate partial flow of activities during currency cleaning

Fig. 11 Expanded problem and solution space of Group 3

problem and solution space created by group 3. Linking far-off ideas leading to the emergence of partial solutions is seen in the highlighted section.

We found that all three groups did a productive and comprehensive exploration of problem space and solution space. However, each group began at a different point (either in problem space or solution space) and traversed along different paths. Consideration of new opportunistic ideas enabled the groups to start new exploration paths when they could not explore the current idea further. Each group used various supports provided by flare-fork collaborative strategy (such as SynAnt strategy, idea categories) as required. Thus we see that opportunistic decomposition is productive in a comprehensive exploration of problem and solution space when accompanied by scaffolds/strategies such as rapid ideation, semantic analogy thought transformation strategy, DSM-based visualization, and categorization.

To summarize, (a) students move back and forth between problem and solution space frequently during the design process, (b) the traversal is via intermediate bridges that link problem and solutions, (c) linking of disparate concepts and categories support the traversal between problem and solution space, (d) irrespective of where the design process began (problem space or solution space), each of the groups did a comprehensive expansion of problem and solution space.

RQ 2: Students' experience of using flare-fork collaborative strategy for designing their product

Students' experience of using flare-fork collaborative strategy can be broadly categorized into 'students' perception of how they used flare-fork collaborative strategy for design,' 'benefits and challenges that the students perceived,' and 'modifications that students desired in the flare-fork collaborative strategy.'

Student perception of how they used flare-fork collaborative strategy for doing design

Students used the activities in the flare-fork collaborative strategy as springboards for new thoughts. Students felt that the idea categories scaffold provided them with a starting point and a new direction for thinking. As one student quoted, *'So that gave me a different thought process - even this kind of ideas will work. Else I was thinking I need to be very specific. That gave me a broader perspective - ok maybe I can go in that direction'*. The synonyms from the SynAnt idea generation activity helped students by giving different perspectives on the design problem. They felt that synonyms helped them identify different sub-problems to be solved. The different definitions of words helped them shift their thinking along new directions and helped them identify previously unimagined causes and scenarios about the design problem.

Students used the flare-fork collaborative strategy as a means of elaborating on the design. Discussing while solving the design problem helped them bring out assumptions, generate complementary ideas, bring variety in solution approach and resolve conflicts in the design problem. Discussions also enabled them to leverage individual domain expertise while exploring the design problem. Creating the DSM enabled students to build on one another's ideas and identify conflicts. Students used the flare-fork collaborative strategy as a means of structuring their thoughts. They did this by using the DSM to facilitate their thinking and for expressing their thoughts. Further categorizing the DSM enabled them to organize their ideas.

Students employed different design exploration methods when using the flare-fork collaborative strategy, such as by posing questions, viewing the design problem by zooming in and out, finding gaps in the DSM to frame requirements, and using user-centered design. As one student stated, *'I think I zoomed in and zoomed out like when I thought of tarnish, I thought we can actually laminate all the currency. Whenever a new idea came, I looked at it from a closer perspective - what the person is trying to say and then I zoomed out and I looked at how is it going to impact like a bigger society'*. Figure 12 depicts the thematic map for how students used the flare-fork collaborative strategy for doing design.

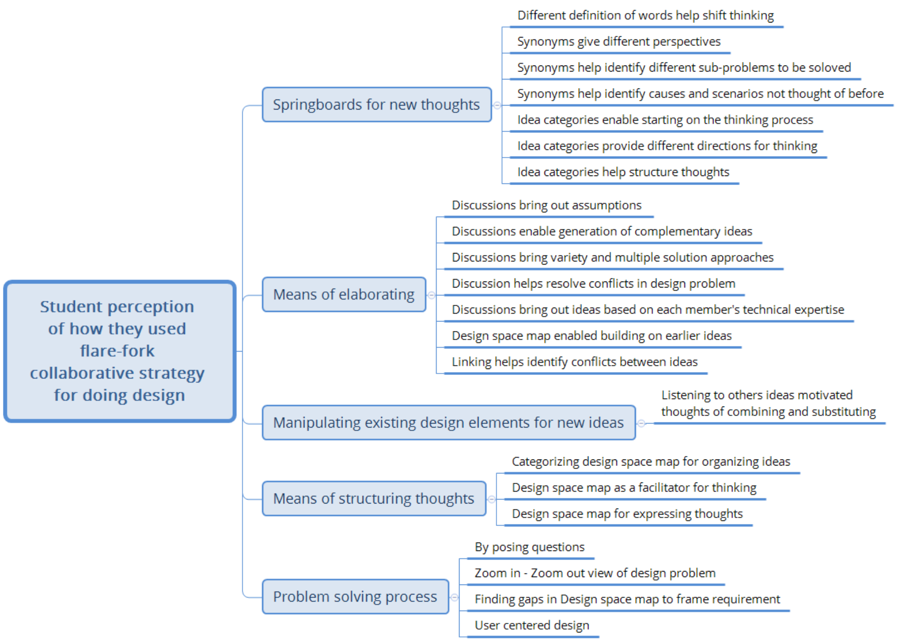


Fig. 12 Thematic map of how students used flare-fork collaborative strategy for doing design

Student perception of benefits and challenges when using flare-fork collaborative strategy

Students found the flare-fork collaborative strategy useful in several different ways. They noticed that using the flare-fork collaborative strategy helped them move from ad-hoc to structured understanding of the design problem. This can be seen from a students' quote, *'when we started, it was kind of a random process. We were not very sure that how do we link that particular term with the main concept. So we were just randomly mapping things like how thoughts came to our mind. But later, when we were able to build upon these the structure became huge. After that, there was some clarity that ok this is one category of things that is another category'*. The DSM visualization and categorization of concepts facilitated the movement towards structured understanding.

While some students felt that the individual ideation activities helped them identify unbiased ideas, others felt that the individual ideation activities enabled each team member to set their own directions. The strategy helped them recognize what expertise they would require for designing solutions. They perceived the orchestration led to equity in participation as seen in the following quote - *'Like when he was speaking, I took a back step and at least let him speak first. So that was a good way of taking turns. Otherwise, only one of us would have just kept talking – one person would have dominated the entire discussion. Here we make sure that it is balanced'*.

Students found the flare-fork collaborative strategy activities engaging. While some found the DSM creation an interesting exercise, others felt that collaborative activities helped them be alert, maintain their motivation and remove inhibition about asking queries regarding the design problem to their teammates.

There were different types of challenges students faced when using the flare-fork collaborative strategy. To begin with, they found it difficult to empathize with the design problem. With the proliferation of online payments, they could not relate to the need for a currency cleaning system. As one student put it, *'initially, I was thinking like why do we need this because we have an alternate system like e-currency sort of things. I was finding it difficult to get over that idea and think about something else because that was occupying my mind so much'*. Some students found it difficult to identify meaningful relationships between different concepts, handle the structure of the DSM, and switch their train of thought to do other activities such as SynAnt search. Since the problem statement was open-ended and did not contain specific details, students mentioned that they initially felt it challenging to take their high-level ideas ahead. However, as they proceeded, the activities, as well as the collaboration, mitigated this.

Modifications desired by students in flare-fork collaborative strategy for doing design

Students felt a strong need for flexible visualization that allows for reorganizing the DSM so that the interconnections are less cluttered. Also, some students felt the need for an alternative hierarchical representation to make the design space more structured. Students suggested using technology as a means to achieve these requirements.

Students had contradictory views on scaffolding. While some students felt that the idea category search cues made them fixate on thinking along only those categories, others felt that they needed idea category search cues that were more specific than the current set. Some students felt that scaffolding search cues and activities such as SynAnt and SCAMPER should be provided only on demand or when the discussion has reached a block. As one student suggested, *'I think when I am stuck with the ideas then some scaffolding regarding this – prompt that you can substitute, combine, then I can go in another direction. But if I am thinking already then I already have a thought process.'*

The appropriate time for accessing external information was another aspect where students felt modification was required. While students agreed that withholding external information at the beginning aided in unbiased ideation, they felt that the availability of external technical information would have contributed by enabling them to evaluate the feasibility of ideas, explore possibilities of an idea and elaborate on the ideas for refinement.

Discussion

For the first research question on how students explore problem and solution space using the flare aspect of flare-fork collaborative strategy, we found that students frequently go back and forth between problem space and solution space. This traversal between the problem and solution space is facilitated by the intermediate space where students do failure analysis of potential sub-solutions and redefine constraints. Dorst and Cross (2001) suggest the existence of a bridge between the evolving problem space and solution space that helps pair problems and solutions. Our observations concur with this insight. Based on our observations, we go a step beyond the bridge and call it an intermediate state that not only helps pair problems and solutions but also pair different problems or different solutions. It aligns with the different co-evolutionary transitions described by Maher and Tang (2003). We observed both problem-driven and solution-driven co-evolutionary exploration (Kruger & Cross, 2006). Irrespective of where the design process began (problem space or solution space), each group did a comprehensive expansion of problem and solution space. This directionality agnostic exploration of the design problem was observed by Wiltschnig et al. (2013). Borrowing from Goel and Pirolli (1992), the DSM can be described as an aggregation of leaky modules or sparsely connected modules compiled with a limited commitment mode control strategy. Unconscious adoption of this strategy allowed the students to proceed with design exploration in a knowledge deficit situation and incorporate abstract opportunistic ideas into the DSM. The co-evolution of problem and solution space via intermediate space throws up several discovered problems (Studer et al., 2018) from the presented problem. These discovered problems capture different perspectives, thereby aiding in the exploration of the problem and solution space. In the study, the discovered problems mainly arose from new operating principles and scenarios.

The opportunistic ideas generated during ideation and DSM creation are an outcome of articulating and connecting the collective tacit knowledge of each collaborating participant, thereby making the knowledge explicit. Discourse, while connecting each participant’s tacit knowledge, provides avenues for discovered problems (Murray et al., 2019) and requirements. The different problem perspectives each of the three groups explored point towards discovered problems. Suwa et al. (2000) describe mediation of the tacit component of knowledge as one way of inventing design issues or requirements. Collaborative DSM creation in flare-fork collaborative strategy provides the mediation mechanism to collate tacit knowledge and externalize it for exploring the design space.

The role of different aspects in problem space such as stakeholders, constraints, scenarios, being a source of different perspectives to view the design problem has been described before (Studer et al., 2018). However, in addition to problem space, all the three groups utilized the solution space aspects such as structure, the principle of operation, and behaviour as sources of the different perspectives of addressing the problem. New perspectives were also triggered from the use of semantic analogy thought transformer strategy.

Students modified the problem in different ways during exploration by using exploration patterns (Studer et al., 2018) for structuring the problem and changing problem characteristics. While idea categories scaffold introduced potential exploration patterns to the students, collaborative DSM creation seems to mediate the use of a combination of exploration patterns. This extends the focused exploration patterns described by Studer et al. (2018).

Regarding the theoretical conjecture, we can see from the findings that combining and interlinking far-off ideas leads to expanding the problem and solution space via partial solutions. Reorganizing ideas by changing context and perspectives leads to the generation of discovered problems leading to the expansion of the design space. Generating new keywords and ideas using semantic analogy thought transformers helped identify new requirements, constraints, and principles, thereby supporting the expansion of the DSM.

Our second research question investigated students’ experience of using the flare-fork collaborative strategy for designing their product. Using flare-fork collaborative strategy for doing design seems to have encouraged good design practices and positive perceptions among the students, increasing the likelihood of them using similar strategies in future designs.

We found that students recognized the value of different scaffolds, activities, and the orchestration method in their design process. For instance, students’ perception of equity in participation, quantitatively substantiated by the evenly distributed percentage of utterances by the students during the entire design process, was attributed to the influence of orchestration.

Some students found it difficult to empathize with the problem. Literature on user-oriented design says that empathizing with the problem is an essential aspect of design that motivates designers to integrate a variety of perspectives. Too much empathy has been reported to lead to less inspired design outcomes, and too little empathy may lead to poorly understood and executed designs (Kim & Ryu, 2014). Collaboration may have played a role in mitigating the ill effects of low empathy for the problem. The role of collaboration in empathy scarce scenarios needs further investigation.

We have identified a few limitations of this research. Flare-fork collaborative strategy focuses mainly on identifying and elaborating the original ideas of the students. The basic assumption is that the prior knowledge that students possess is sufficient to begin the exploration process, and the collective knowledge of collaborators can mitigate the information gaps. However, moving forward, students need to evaluate and restructure their DSM and subsequent designs to accommodate factual knowledge. Flare-fork collaborative strategy does not support this aspect of design.

The empirical study covered only three groups who were purposively selected based on their availability and branch of engineering. Additionally, while two groups were triads, one group was a dyad. The number of participants in a group influences the richness of the DSM. The triads cover more concepts across the different aspects of the problem and solution space than the dyad. However, the detailed analysis of the participant interactions and generated artifacts enabled the researchers to uncover how students used the flare-fork collaborative strategy to do design and their design experience.

Several studies have investigated design exploration using a different framework (Goel & Pirolli, 1992; Guindon, 1990; Kruger & Cross, 2006; Maher & Tang, 2003). There is, however, a lack of a systematic quantifier for the expanded problem and solution space. Analyzing exploratory design ideation (AEDI) (Hay et al., 2020) is worth exploring as a framework for quantifying problem and solution space expansion.

There are several modifications we intend to make for the future version of flare-fork collaborative strategy. We observed that students did not integrate new knowledge emerging from their collaborative discourse into the DSM. Instead, they required regular prompts from the facilitator to do so. The reason could be that students have a lower commitment to the verbal nature of statements generated during problem structuring activity of design than written output during problem solving activity (Goel & Pirolli, 1992). They may therefore not be inclined to record the verbal discussion in the DSM. Flare-fork collaborative strategy would need to address this reluctance to record verbal discourse by incorporating regular prompts or structured scaffolds.

From the research question on students' experience, we found that students felt a need for flexible visualization, easy editing, and reorganization of parts of the design in the DSM. Reorganization of information for better information management and complexity reduction is crucial for a design support environment (Ball et al., 1997; Guindon, 1990; Visser, 1994). The non-editable paper version subtly constrains free addition to the DSM, making it counterproductive to expanding the problem and solution space. On the other hand, a digital representation is easily editable, removing the barrier to adding more concepts to the DSM. Accordingly, we designed activities on a smartboard (SAMSUNG Flip 2 WM65R) to be used as a collaborative space. We used the IHMC CMAP tool for creating the DSM.

Regarding scaffolds such as idea categories and exemplar links, students felt they were helpful but a source of fixation at times. On-demand scaffolds that the students can control may mitigate the fixation effects of such scaffolds. Given this, we used flashcards using PowerPoint to render these scaffolds. Flashcards allow students to control when and how to use the scaffolds during the design process. We used PowerPoint to implement the

SynAnt worksheet to simplify collating synonyms and antonyms and free students' cognitive resources for actual idea generation. The purpose of digitizing most parts of the intervention was to evaluate if the technology version provides sufficient flexibility in manipulating design artifacts. Going ahead, we would like to create customized software to provide a seamless collaborative design experience for students.

Conclusion

The contribution of this paper is the flare aspect of flare-fork collaborative strategy that supports opportunistic design approach towards solving ill-structured problems. While design co-evolution and opportunistic decomposition have been extensively studied, this study brings the two ideas together in the flare-fork collaborative strategy. The paper has also attempted to describe how mediating processes of combining and interlinking distal ideas, reorganizing ideas by changing context, perspective, and new keywords contribute towards expanding the problem and solution space. The paper has also attempted to gain insights into student perceptions about doing design following flare-fork collaborative strategy.

The future direction of research would be to analyze the stopping mechanism when pursuing an opportunistic idea collaboratively during design co-evolution. Epistemic uncertainties can force designers to temporarily abandon the focus on one idea and move to the next idea. Insights into the mechanisms designers follow when uncertainties beset them can also help formulate effective scaffolding to design support tool.

Abbreviations

DSM: Design space map; PS: Problem space; SS: Solution space; IS: Intermediate space.

Authors' contributions

The first author has done the design, development and evaluation of Flare-Fork collaborative strategy under the guidance of the second author. The first author drafted the manuscript and the second author reviewed it and suggested modifications.

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Declarations

Competing interests

The authors declare that they have no competing interests.

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