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Situation, Problem, and Solution

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Design from Waste Materials: Situation, Problem, and Solution

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Abstract: *Drawing on Sarasvathy's theory of effectuation, the co-evolution model of design thinking, and Dewey's pattern of inquiry, we investigated the potential of reusing heterogeneous material scraps in industrial design to create environmentally sustainable products. We present a descriptive model of the design process from a longitudinal study in a Master of Science industrial design program. The findings show the importance of problem-forming and the reshaping of situations through effectual reasoning. The study contributes to the field of sustainable design by offering a framework for reusing material scraps and fostering effectual thinking in industrial design education.*

Keywords: *Co-evolution; effectuation; sustainability; industrial design; design process*

Introduction

Sustainable development means meeting the present's needs without compromising future generations' ability to meet their own needs (Fleming, 2013, p. 37). Since Earth is a limited system, depleting its resources is unsustainable. A key issue when designing for sustainability is how to make new products without depleting Earth's natural resources. We need ways to make new products from the limited resources available or in use, such as recycled and reused materials, rather than virgin materials.

Material wastes and scraps are significant problems for many industrial production companies. Even in a tiny country like Denmark, industrial production companies produce over 1.1 million tons of waste per year (Madsen et al. 2019). And although researchers have investigated upstream solutions, such as distributed manufacturing, open design, and design for value recovery (van Dam et al., 2020), design researchers have paid too little attention to reusing heterogeneous scrap materials in new products, even though it is needed.

For example, Ellegaard Components a Danish company that makes conveyor belts. Their production process produces scraps of textile-reinforced plastic and rubber, that are discarded because of the material's heterogeneous composition. They are too difficult to recycle through conventional chemical and mechanical processes. What to do about these scraps is a problem for Ellegaard Components because disposing of them in a landfill is not environmentally sustainable.

Today, industrial production companies typically analyse industrial wastes and scraps in terms of their recovery potential for recycling. However, the European Commission found that new product development's design phase determines 80% of the CO_2 emissions that industrial production creates (EU Science Hub, The European Commission). Reusing materials with minimal adaptation may save significant energy compared to recycling. For example, Ali, Wang, and Alvarado (2019, p. 1042) found that material reuse saved 40% capital costs and 67% energy consumption by designing products from industrial scraps compared to using recycled materials.

There are significant environmental benefits to reusing scraps rather than recycling them. However, reusing heterogeneous material scraps is challenging, because they may vary along several parameters, such as shape, size, surface, mechanical properties, physical properties, and sensorial properties (see Pacelli, Ostuzzi, & Levi, 2015, pp. 9091). So, designing with heterogeneous material scraps means starting each design project with a situation, that represents a unique set of constraints.

The design process typically emphasises concept design first and production second. Consequently, it assumes that there is an infinite supply of virgin materials. But design for sustainable development cannot ignore the limited materials and production processes it has available in its local situation. Designers need to solve problems that are embedded in local situations. Our objective was to start with the assumption that designing products from virgin materials will inevitably become extinct, then leverage the students' problem-based project work to see what our students could discover (see Laursen, 2013).

Research Question and Objectives

We investigated this issue by conducting engaged scholarship in design education to answer the research question: How do industrial designers design with heterogeneous waste materials, such as off-cuts, rejects or other production scraps? We answer this research question with the following contributions:

- Insights into a design process, based on the co-evolution model of design thinking (Dorst & Cross, 2001), Dewey's (1991) pattern of inquiry and Sarasvathy's (2008) theory of effectual entrepreneurship.
- A descriptive model of a student team's design process where the situation, problem, and solution co-evolve.
- An outline of an interdisciplinary approach that integrates design activity and effectual entrepreneurship that links design practice to deeper organisational change and the shaping of new markets.
- Lines of future research into effectual design.

Design from Heterogenous Waste Materials: Rejects and Scraps

Earth is a limited system. At some time, we will run out of virgin materials. A good strategy is using recycled materials to make new products. But recycling is a limited approach because often it is down-cycling and the capacity for recycling depends on the material. It is not feasible to recycle some materials because they are heterogeneous or because the recycling process itself emits too much CO_2. So, there is value in reusing materials that are too difficult to recycle and too valuable to throw away.

The idea to make new products from reused materials is not new. However, embedding material reuse in the industrial production process from the beginning is under-researched. A promising direction for research is Pacelli et al. (2015) procedural method for analysing the feasibility of reusing industrial scraps to improve the economic and environmental value of products. Pacelli et al. (2015, p. 79) divide industrial wastes produced by manufacturing processes into scraps and rejects. Scraps are precisely predictable since production companies produce them in known proportions to specified parts. Rejects are only statistically predictable since they are usually defective parts that cannot meet specifications. Pacelli et al. (2015) aim to support designers to compare the value of manufacturing a product from scraps to manufacturing the same product from virgin materials.

Pacelli et al.'s (2015) model has three phases (1) optimisation, (2) analysis, and (3) design. The first phase (1) aims to improve the manufacturing process to reduce scrap production. However, despite optimisation efforts, the process may still produce a predictable quantity of scrap. The second phase (2) begins with identifying the scrap's characteristics, machining limitations, and potential for reuse in a new product. Designers should identify the range of operations for subsequent machining, combination with other virgin raw materials, and the need for joints and connections. Phase three (3) implements a design process to create a specification for a new product. Then the designers should compare the new product's value to either producing the same product made using virgin raw materials, recycled materials, or maintaining current waste management processes. The optimisation phase is important because it shows that the production process is itself able to be incorporated into the design process as a focus of design activity.

We took Pacelli et al.'s (2015) model as a useful point of departure for an integrated design process. Our approach is based on Sarasvathy's (2008) theory of effectual reasoning, that works as a system with limited resources, a given set of means.

Effectual Reasoning: Working from Limited Means

By focusing on what can and cannot be done with resources already at hand, industrial designers can act effectual to construct new markets for valuable new products made from material scraps. Effectual reasoning is a type of human problem-solving that starts with limited means and non-predictive control (Sarasvathy, 2008). In an entrepreneurial context, the goals emerge organically because of the limited means and the circumstances. Thus, rather than defining a specific plan and goal and sticking to it, the focus is on what means are available now. Sarasvathy (2008) identifies five heuristics that characterise effectuation:

1. *Bird-in-hand:* Continually distinguish means within and outside your control, and work only with things already within your control, such as who you are, what you know, and whom you know.
2. *Affordable loss:* Invest only what you can afford to lose, whether the investment is in terms of money, time, or other resources. Keep the downside within your control.
3. *Crazy quilt:* Work with whoever wants to work with you. This sets in motion a process of stakeholder self-selection. These stakeholders each provide commitments that underwrite the immediate next steps of the process. This brings the proximate future within the control of the venture.
4. *Lemonade:* When you encounter contingencies outside your control, work creatively to transform them into opportunities, for example by recombining them with a bird-in-hand and crazy quilt strategy or by reworking your affordable loss and what you can do with it. This converts the unpredictable itself into a resource.
5. *Pilot-in-the-plane:* Co-create the future of both your organisation and its environment.

Each of these effectual heuristics enables decision-making based on a logic of non-predictive control (Sarasvathy & Venkataraman, 2021, p. 133). Effectual reasoning is important for designers doing design with scraps as they work with limited means and need to let the goal emerge organically. Sarasvathy and Venkataraman (2021) explain:

> Effectuation enables individuals and organisations to go beyond an adaptive to a co-creative stance toward their environments. In other words, organisational change need not only be in reaction to environmental changes, but can also be a proactive and interactive reshaping of environments. (p. 133)

Knowledge on how to design from heterogeneous scraps is underdeveloped. So, the problem involves effectual reasoning efforts: working from limited means, where the situation can be proactively designed. To understand how this connects to a design process we turn to the co-evolution model of design thinking (Dorst & Cross, 2001) and Dewey's (1991) pattern of inquiry.

Co-evolution: Designing a Product

The basic theory is the co-evolution of problems and solutions. Design researchers often cite Mayer and Poon's (1996) paper as the origin of coevolution in design theory. Meyer and Poon represent co-evolution diagrammatically (Figure 1).

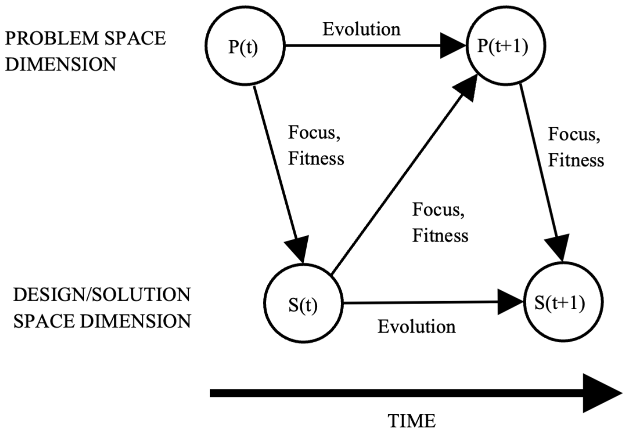

Figure 1. Mayer and Poon's diagrammatic representation of co-evolution. © 1996 Mary Lou Meyer and Josiah Poon.

Co-evolution is important because it highlights how designing involves more than specifying solutions to given problems, it also involves problem-finding and problem-forming. This point is consistent across design theory from rationalism (Simon, 1995) to pragmatism (Schön, 1995). For example, Dorst and Cross (2001) write:

> It seems that creative design is not a matter of first fixing the problem and then searching for a satisfactory solution concept. Creative design seems more to be a matter of developing and refining together both the formulation of a problem and ideas for a solution, with constant iteration of analysis, synthesis, and evaluation processes between the two notional design 'spaces' — problem space and solution space. (p. 434)

However, Meyer and Poon's theory investigates how a computer might design, so it ignores the situation that the Earth is a limited system. It assumes that solutions have an infinite supply of virgin materials available to produce the solution.

Dorst and Cross's (2001) problem-solution co-evolution model of design practice is highly cited in the literature. Later, Dorst (2011, p. 531) claims co-evolution might connect design practice to deeper organisational change and the shaping of new markets. Recently, Crilly (2021a, 2021b) proposed a conceptual expansion, such as three systems coevolving or several systems evolving at different levels (Figure 2).

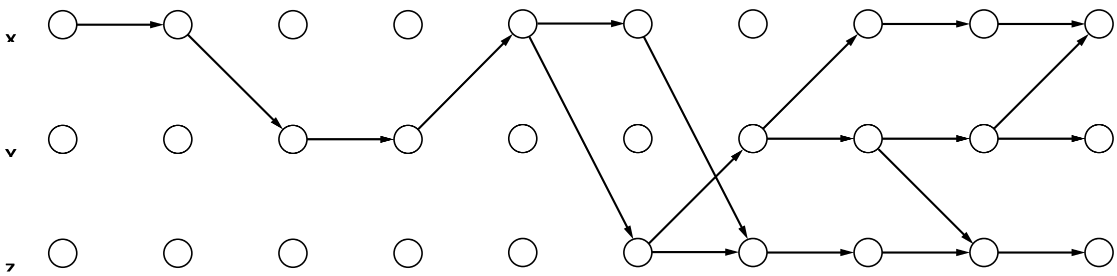

Figure 2. Crilly's illustration of a process where three systems (X, Y, Z) are co-evolving. © 2021 Nathan Crilly.

Crilly's model is significant because it opens new directions for co-evolution research. We aimed to investigate Crilly's proposal of a process where three systems co-evolve, by modelling a process involving the possibility of problem, solution, and situation co-evolution. In our case, we take the situation as capable to be shaped by effectual reasoning.

Situation: A Pragmatic Inquiry

In research the design process is usually described as adapting to changes in the environment that are exogenous to the designers' own activities. In this paper, we conceptualise design activity as a time-based process, acting on situations in ways in which the situations themselves are shaped and constructed through the design activities in time. In our case, the situation is the effectual aspect of industrial design.

Schön's concept of reflective practice resonates with the concept of co-evolution. Schön (1995) discusses design as a reflective conversation with the materials of the situation. Schön's approach is deeply influenced by Dewey's pattern of common-sense inquiry, and this is where the concept of the situation comes from in our theory (Schön, 1992a, 1992b).

The concept of the situation is important because Meyer and Poon's theory is about how a computer may design not how a person might design. But real design occurs in a real situation with its real qualities. "We never experience nor form judgments about objects and events in isolation," Dewey (1991, p. 72) writes, "but only in connection with a contextual whole. This latter is what is called a "situation." According to Dewey (1991),

> Inquiry is the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into a unified whole. (p. 108)

Research Design and Methodology

We conducted engaged scholarship (Van de Ven, 2007) of students' design activity within an MSc. Industrial Design module. Our study was centrally concerned with how change unfolds over time in the design process. Our focus was on the progressions of activity that industrial design student teams effectuate as the design process develops over time. We took an event-driven approach to describe how the temporal order and sequence of events unfolded while the change occurred.

Our research design has four parts (Figure 3). The problem of reusing heterogeneous scraps that needs a solution in terms of an answer to the research question. A theory of co-evolution of situation, problem, and solution, and a model of the design process (Figure 6).

Our focus was on the design students' activity. The students' age falls within the range of 20-30 years and their cohort is in their 2nd semester of education in the MSc Industrial Design programme. We divided the cohort of 40 students into six teams of five students.

We gave the students the problem, then they investigated it through their problem-based project work (Laursen, 2013). The teaching and learning activities included individual group supervision as well as short weekly status meetings with the whole cohort. The assessment was by oral examination. The project duration was 10 weeks fulltime.

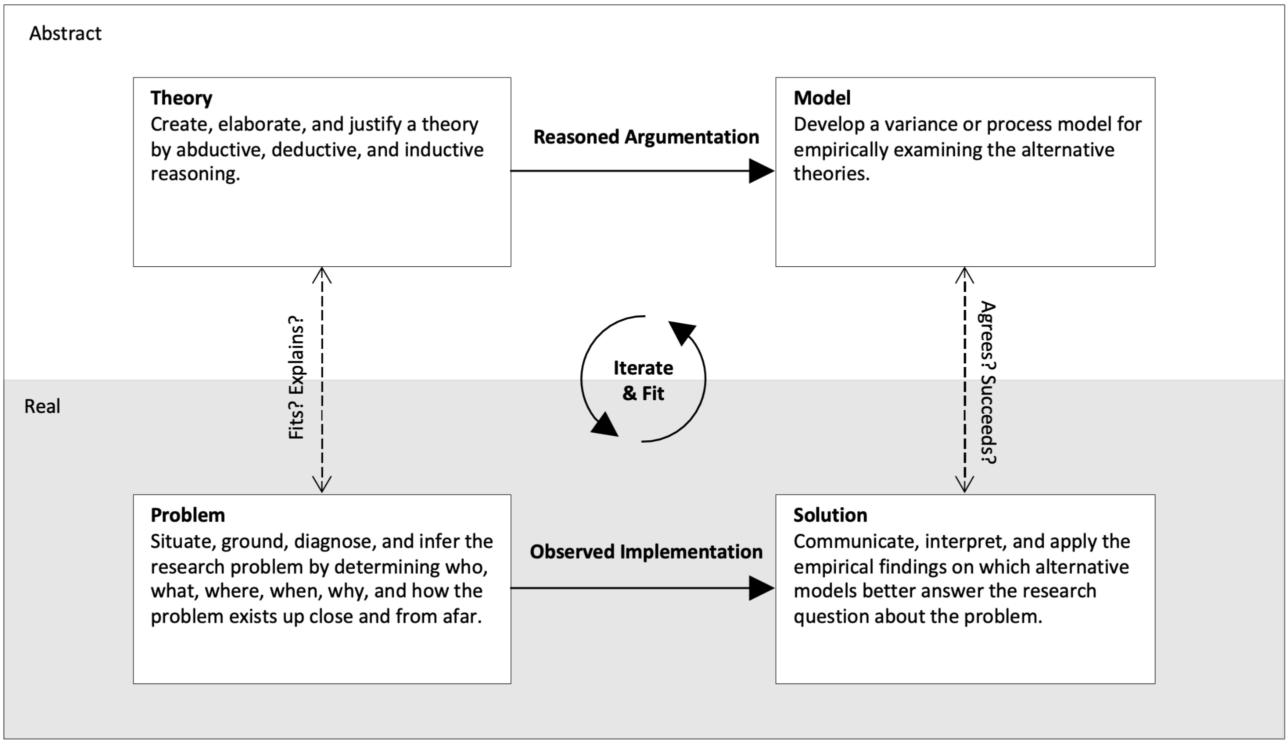

Figure 3: Engaged Scholarship Research Design adapted from Van de Ven (2007)

Teleological process theory and its application to the study

Our study is informed by a teleological process theory that views the process as the purposeful enactment of actions to achieve a given goal. We assume that there are several equally effective ways to achieve the goal, so, rather than depicting the process as a necessary sequence of stages, we posit a set of functions the team must acquire to realise its aspirations. According to Poole, Van de Ven, Dooley, and Holmes (2000).

> "Teleological models may exhibit stages, but the stages do not have to occur in a particular order; stages must occur and cumulate to satisfy the final goal or form of the process, but the order in which they are satisfied is not particularly important." (p. 95).

We provided students with a short handout that summarised the key aspects of the design process and effectual reasoning. This handout was not prescriptive, students did not have to follow it. Also, students were already familiar with effectual reasoning from previous studies. Students were well prepared to act independently through their training in the AAU model of PBL (Krogh & Jensen, 2013).

The research project involved several stakeholders, including students, teachers, industrial production companies, managers, and researchers. We aimed to see organisational life from the students' perspective. However, rather than assuming a detached view, we actively took part in the activities and situations being studied through our role as the student's teachers. In taking this view, the primary investigator needed to act reflexively as they stepped into and out of several roles.

Data Collection and Analysis

We collected longitudinal data by observing the change events of six teams as they occurred in real-time, so we did not know in advance which teams would achieve the best outcomes. Therefore, during the fieldwork, we did not know which information was most important and which was not. However, observing the change in real-time has the advantage that not knowing the outcomes in advance reduces a potential source of bias because of overlooking events that might not fit the central narrative.

Figure 4. Semi-structured group interviews with card-sorting activity

We collected field notes and documents and conducted semi-structured interviews at the mid-point and end of the project (Figure 4). The second interview also involved an activity to map out the students' design process (Figure 5).

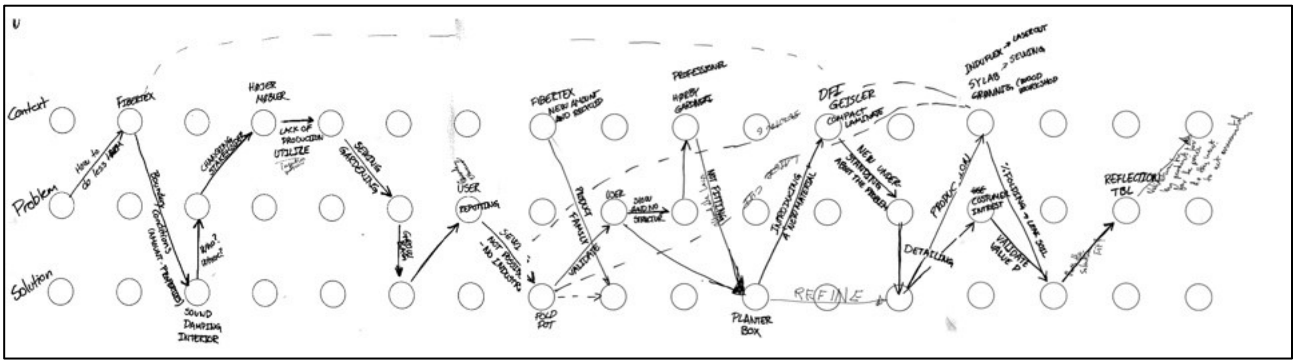

Figure 5. A student team's map of their design process

We studied recurrent conjunctive progressions of parallel streams of designerly and entrepreneurial activities, with events in one stream relating to and influencing events in the other stream (Van de Ven, 2007, pp. 201-202). The events are conjunctive because the outcomes of earlier events become incorporated into the later ones. And the events are recurrent because the designerly and entrepreneurial activities show iterative progressions of repeating strings of events. This structure permitted a parallel, synchronic, and diachronic research design (Van de Ven, 2007, pp. 208-210). This research design allowed us to compare the combination of events from three spatial and temporal axes.

The sample size was determined by the number of observed events got during the change process. The students worked full-time in their groups on their projects over 10 weeks. All the groups took part in short weekly update meetings where all teams reported on progress and shared information. We also recorded field notes and reflections about the process as it unfolded. This allowed for observations at various levels of granularity and temporal durations.

We analysed the data by parsing the events into phases that represent coherent periods of activities, subsuming a series of events into a sequence. This provided temporal divisions in the case studies that allowed time series analyses to track temporal dependencies among events that identify patterns of change across the cases.

Adoption of deductive, inductive, and abductive modes of inquiry

We adopted deductive, inductive, and abductive modes of inquiry that are grounded in theory or data. We adopted a deductive theory-driven approach that draws on Sarasvathy's (1998) model of effectual reasoning and Dorst and Cross's (2001) problem-solution co-evolution model of design practice. These two theories complement each other since they share basic ideas from Herbert Simon's (1996) Artificial Science and Pragmatist philosophy (Dewey, 1991). We also adopted abductive inquiry to develop propositions that explain the iterative progressions of designerly and entrepreneurial activities over time. And we adopted inductive inquiry to build grounded theory from the data. Consequently, we moved back and forth between deductive, inductive, and abductive modes of inquiry during the study (Van de Ven, 2007, p. 207).

We used Sarasvathy's five entrepreneurship heuristics and the six design activities to provide a focus for observing the change process. We used these concepts to describe the activities being observed. We distinguished incidents from events. Incidents are operational empirical observations. Events are abstract concepts of sets of incidents. We translated the stream of incidents into a sequence of events. We enhanced the validity of classifying the incidents into events by checking whether the primary investigator's coding system coincides with the student's perceptions of events. Following Van de Ven (2007), we define a qualitative datum as:

> (1) a bracketed string of words capturing the basic elements of information; (2) about a discrete incident or occurrence (the unit of analysis); (3) that happened on a specific date; which is (4) entered as a unique record in a qualitative data file; and (5) is subsequently coded and classified as an indicator of a theoretical event (p. 218)

We used the constant comparative method, visual mapping, and temporal bracketing to tabulate and organise the data (Van de Ven, 2007, p. 220). The constant comparative method proceeds abductively to sift through the various incidents and derive categories from the ground up. Visual mapping uses graphical representations to display the information simultaneously and permit boundary crossing. Temporal bracketing arrays events over time in phases of activities, to show continuities and discontinuities within and between periods within the design process.

Findings and Contributions

In this section, we present data about one of the teams' projects. The data reports the students' design process, beginning with investigating the local situation to identify sources of industrial scrap material, through problem forming, solution growth and refinement, and situation determination. Figure 6 shows a descriptive model of a student team's design process. And Extract 1 reports from an interview where the students describe an event within their process where the situation, problem, and solution co-evolve.

Our analysis of the data shows the students' engaged in both designerly and effectual activities simultaneously. Extract 1 reports an event where the situation, problem and solution are co-evolving, and the students enacted effectual design. This extract corresponds to t_{12}—t_{13}, as illustrated in the descriptive model (figure 6).

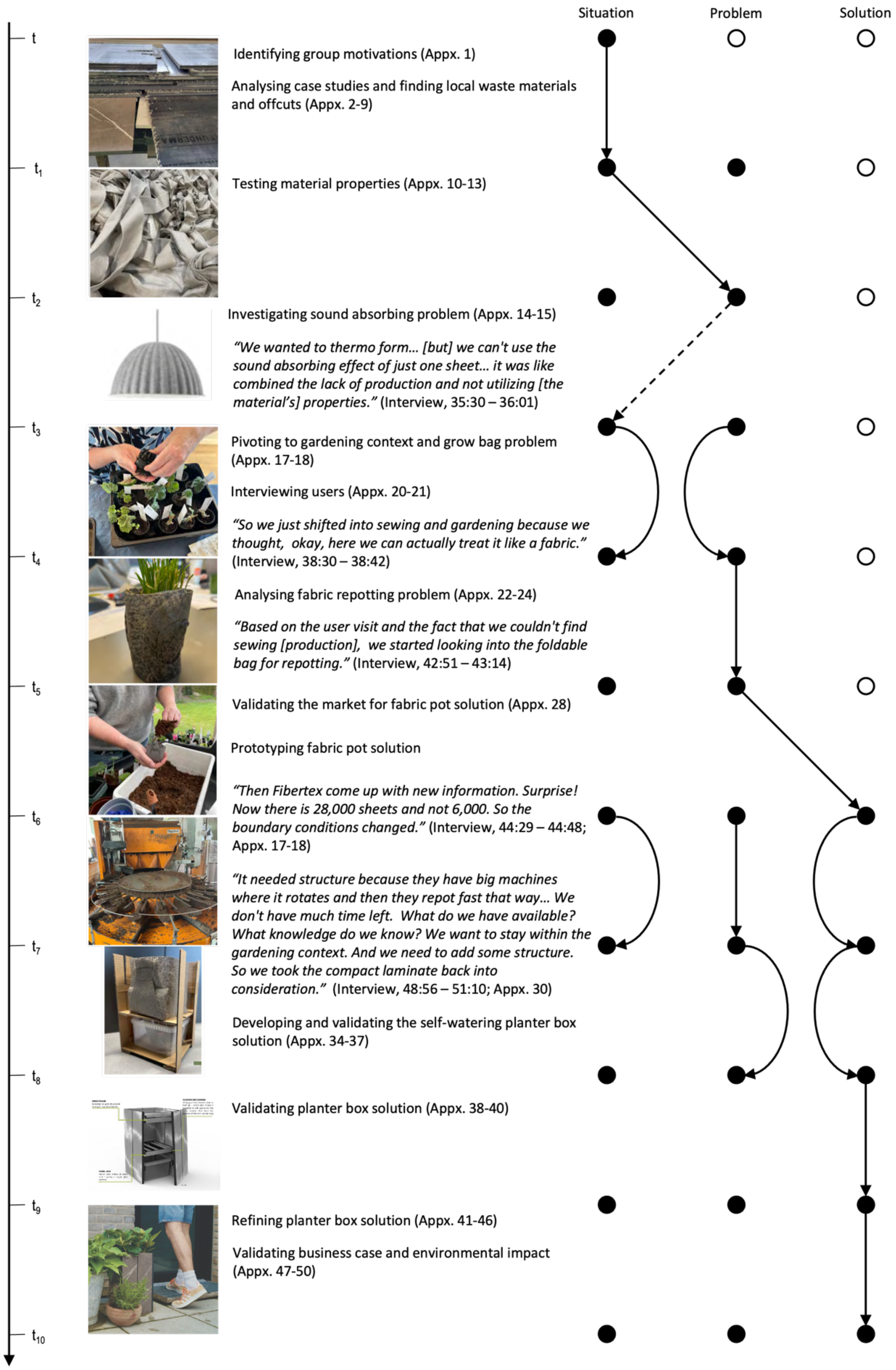

Figure 6: Descriptive model of a student team's design process where the situation, problem, and solution co-evolve. © 2023 First Author.

Extract 1. Co-evolution of situation, problem, and solution

[44:29 - 44:42]	What happened was that we got some new answers from Fibertex… Surprise! Now there are 28,000 sheets [of scrap material] and not 6,000… So, the boundary conditions changed.
[48:24 - 48:26]	And then we tried to change the context, didn't we?
[48:56 - 49:15]	And then we thought, okay, let's try and go out to the horticulture [market]. First of all, because we have more sheets so maybe there's a possibility of having a bigger market.
[49:16 - 49:37]	And also, it was within gardening and so on. But here we had the same problem. If we wanted to make a pot or redesign the pot, it needed structure. Because they have big machines where they place the pots in like these aluminium beams.
[49:38 - 49:55]	And then it rotates and then they repot fast that way. And this would not be able to fit and hold the dirt and the plant at the same time without falling through. So, they had already machines that it needed to fit in order to be used.
[49:55 - 50:04]	So, both of these [factors] made us try to find a new solution space.
[50:43 - 50:50]	And then we find the planter box.
[50:52 - 51:10]	Affordable loss. We don't have much time left. What do we have available? What knowledge do we know? So, we want to stay within the gardening context. And we need to add some structure probably to the material. [So, we took] the compact laminate back into consideration.
[52:31 - 52:51]	The whole thought was, okay, we found this planter box. We were able to add structure to the Fibertex material through the compact laminate. Okay, so how can we make a planter box that differentiates a bit on the market?

The value in distinguishing the situation from the problem and solution is that it changes the situation from an exogenous environment to an endogenous artefact. From this point of view, designers shape situations and construct them through their design activities. However, the activities and methods for shaping situations are not the same as those for designing products. In our study, we have used the principles of effectuation to describe how design students might shape the situation of design projects. We claim that integrating design theory and effectuation theory will do better than the status quo because it links design practice to sustainability and limited resources issues. Our research presents new data that address the "core" of design thinking, namely Dorst's (2011) concept of Abduction-2

> The creation of a new frame through the investigation of themes, in a deeper transformation of the organisations' own practices. This last level is where design-based practices and organisational innovation are most intimately linked. This is where design practices and the knowledge that has been built up over almost 50 years of design research can directly relate to processes that have been described in terms of 'entrepreneuring' (Steyaert, 2007) and 'effectuation' (Sarasvathy, 2008) in management literature. (p. 531)

We argue our findings support the claim that the problem, solution, and situation evolve together within the design process. We modelled effectual design as a system of three components—situation, problem, and solution—interconnected by three balancing feedback loops, and three reinforcing feedback loops.

Further research is needed to explore new methods for design effectuation. Comparing students' problem based and project-oriented education with professional designers' practice can provide valuable insights into the adaptability and effectiveness of the co-evolution model of design effectuation. Additionally, investigating the interdisciplinary approach proposed in the study, which integrates design activity with deeper societal and sustainability issues.

Building on the findings reported in this paper, a comparison of all the teams' design processes can identify both similar and different aspects, revealing further examples of situation-problem-solution co-evolution in the context of sustainability. This deeper understanding could contribute to the development of effective strategies for creating environmentally sustainable products and shaping new markets that prioritise the reuse of materials.

Conclusion

Effectual design offers a distinct approach to industrial design by emphasising the skills, knowledge, and competencies that differentiate it from craft work. It recognises the need for designers to proactively reshape situations, understand limitations and construct new markets. By applying effectual reasoning, designers can leverage existing resources and focus on problem-solving based on non-predictive control. Effectual design acknowledges the limitations of traditional recycling methods and highlights the value of reusing materials that are difficult to recycle but too valuable to discard. By considering the co-evolution of situations, problems, and solutions, designers can navigate the complexities of the design process and shape new markets for products made from scraps, incorporating entrepreneurship and design thinking to validate viable products that address economic, environmental, and social dimensions.

Effectual design offers a proactive approach to sustainable industrial design. Our research suggests that combining the co-evolution model of design thinking and effectual reasoning provides students with a holistic understanding of how design and entrepreneurship intersect. This integration equips students with adaptable and relevant entrepreneurial skills within the design field, enabling them to shape new markets and create feasible new products from scrap materials. The integration of these two approaches fosters innovation, creativity, and the ability to navigate uncertainties and complexities in real-world entrepreneurial settings.

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