An Approach to Assist Designers Collaborating with Scientific Researchers towards the Development of Experimental Tools and Practices

by

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Abstract

Since consumer experience shifts from mass consumption to context and personalization consumption, we are now focusing on the ecosystem of services, experience and solution instead of only paying attention to the product itself. Openness as one of the methods enables possibilities for a set of open practices. These practices can achieve additional benefits and solve needs based on context and personal needs of others who are outside of the current closed development system.

Currently scientific researchers keep looking for collaboration to maintain their productivity. However, the increased specialization of individuals working in laboratories goes against the current move toward understanding system in the sciences (Binz-Scharf, Kalish, & Paik, 2015). That leads to quite chaotic, irritating, unpredictable and turbulent situations, especially in workplaces and labs during practices and experiments. In these circumstances, scientific researchers often face the situation when individuals cannot streamline experiments or practice processes, wasting a lot of time to execute the inefficient processes.

In that case, helping scientific researchers to solve their problems and enhance their collaboration efficiency becomes a great potential. By utilizing local institutional resources, scientific researchers from different backgrounds could solve problems for each other by applying design methods and open innovation (Aitamurto, Holland, & Hussain, 2015) to help them develop experimental tools and practices.

This study researches the logic of design, which is different from the logic of methods scientific researchers use. This study also researches different approaches of design methods to define problems and develop an approach for collaboration of designers and researchers. This

approach is a guideline which allows scientific researchers to refine the problems they meet in experiments and help them develop a plan for a collaborative problem-solving process. This tool should be created based on design methods which offer a lot of ways to define problems and develop plans. Design methods also can offer great potential to deal with problems in experimental tools and practices from different areas in academia. In that case, an approach is developed to assist designers collaborating with scientific researchers towards the development of experimental tools and practices.

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Even though this thesis development process is a long journey, I enjoy the excitement of discovery and the moment of struggling. These are the priceless treasures in my life.

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Chapter 1 Introduction

1.1 Problem Statement

Currently, scientific researchers tend to research interdisciplinary issues. Most of the time, they need to solve problems they meet in experiments and practices by collaborating with others. Academic interest in interdisciplinary scientific collaboration is growing considerably (Stokols, 2006). Researchers should deal with problems in experiments and practices personally. Instead of buying instruments from suppliers or companies, in most of the cases, those researchers tend to solve the problems by themselves or find people to collaborate with. However, the collaboration is filled with problems silo challenges and cross touch points inside the organizations (Lockwood & Papke, 2017). That leads to quite chaotic, irritating, unpredictable and turbulent situations, especially in workplaces and labs during practices and experiments.

Usually, the problems researchers meet are uncommon, and they have to solve them by themselves. Sometimes, due to limitation of knowledge, they tend to find designers who can help them. Nevertheless, it is hard for designers understand the problems because usually researchers define the problems by themselves without a standard procedure.

There is a popular statement about emphasizing how important laying the proper groundwork then attempting to solve the problem is. This statement is usually attributed to the great designer Charles Eames:

“In the statement of the problem lies the solution.”

That means different statements of the problem lead to different solutions. We cannot accept the problem at face value. We have to find the real problem(Pressman, 2018). When researchers need to collaborate with others, an approach is needed to design for them to assist designers to organize their problems in a systematic way. Universities do not have such tools or strategies to help researchers find resources and offer a process to solve problems right now.

In order to deal with complex problems and offering solution on time, design takes on a coordinating role and relies on the knowledge of others(Cross, 2011). Design methods offer approaches of problem solving from different disciplines. The reason the researchers use design methods as approaches is because Buchanan (1992) thought design has no subject matter—that's what makes this a powerful discipline and designers make our subject matter. Open Innovation, as a popular approach among organizations globally, encourages the use of external knowledge and external partners to accelerate innovation (Yapa, 2018). Based on design methods and open innovation, the proposed problem refinement tool should help designers to promote communication and collaboration of different researchers and improve efficiency of experiments and practices in academia.

1.2 Need for Study

Scientific researchers face more problems than ever during their practices and experiments because academia researches are becoming complexity and interdisciplinary. Academic interest in transdisciplinary scientific collaboration is growing considerably (Stokols, 2006). In some cases, researchers need designers to collaborate with them. The tools using design methods to help designers to refine researchers' problems and help them to collaborate more easily is new for academia. Since design logic and methods are new to many researchers, there is no standard approach to helping them to understand their problems better. This creates a need for standardizing approaches to develop a tool to assist designers and researchers to refine problems.

This study will focus on researching the differences in the logic of design and science, and problem definition in design methods as well as developing an approach to assist designers collaborating with scientific researchers towards the development of experimental tools and practices.

There are many theories of design methods to help designers define their problems, but none of them are designed specifically for researchers. This study will develop a specific method to help scientific researchers define problems. The approaches and methods developed in this research will be demonstrated by helping researchers in NCAT (National Center for Asphalt Technology) redefine their problems from experiments. While the method of defining scientific research problems, in this study, will be illustrated by refining problems from NCAT's researchers, the approach that is developed from this research could apply to most of academia areas.

1.3 Objectives of Study

- Analyze the difference between the logic of science and the logic of design;
- Study problem solving process;
- Study the open design process and how designers work with others;
- Develop an approach to promote scientific researchers' problem-solving process;
- Study the structure of collaboration between designers and researchers;
- Help designer to identify and refine scientific researchers' problems to develop experimental tools and practices.

In order to develop an approach for the problem-solving process for scientific researchers based on design methods and open innovation, the literature review includes the study of design methods, open innovation, problem solving processes, collaboration, interdisciplinarity and crossdisciplinarity.

1.4 Definition of Terms

Abductive reasoning: also called abduction or retroduction, starts with an observation or set of observations, then seeks to find the explanation (Wikipedia, 2019a) and may or may not including working principles (Dorst, 2011).

ASTM International: American Society for Testing and Materials, is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services (Wikipedia, 2019b).

Cross-disciplinary: of, relating to, or involving two or more disciplines ("Dictionary and Thesaurus | Merriam-Webster. (n.d.)," 2019).

Crowdsourcing: a problem solving and production system in which a crowd is enlisted to help solve a problem defined by a system owner (Aitamurto et al., 2015).

Deductive reasoning: is the process from one or more premises to reach a logically certain conclusion (Wikipedia, 2019c) based on the working principle (Dorst, 2011).

Ill-structured problems: possess multiple solutions, solution paths, fewer parameters which are less manipulatable, and contain uncertainty about which concepts, rules, and principles are necessary for the solution or how they are organized and which solution is best (Jonassen, 1997).

Inductive reasoning: is the derivation of working principles from the premises which are viewed (Wikipedia, 2019d) and the result which is observed (Dorst, 2011).

Interdisciplinary: involving two or more academic, scientific, or artistic disciplines ("Dictionary and Thesaurus | Merriam-Webster. (n.d.)," 2019). It is organized in two hierarchical levels and connotes coordination of a lower level from a higher one (Max-Neef, 2005).

Open Design: the state of a design project where both the process and the sources of its output are accessible and (re)usable, by anyone and for any purpose (Boisseau, Omhover, & Bouchard, 2018).

Open Innovation: the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively (Chesbrough, 2006). Its knowledge transfers are usually limited to non-disclosure agreements and contractual frameworks (Marais & Schutte, 2009).

Well-structured problems: constrained problems with convergent solutions that engage the application of a limited number of rules and principles within well-defined parameters (Jonassen, 1997).

1.5 Assumptions of Study

It is assumed that all of the information gathered during this research is accurate and appropriate for this thesis. It’s also assumed that the research within this project will be adapted to the scientific researchers’ needs of development of experiments tools and practices. In addition, this research assumes scientific researchers use the logic used in science to solve problems and demonstrate the solutions. This assumption is based on trends in transdisciplinary work; collaboration between researchers becomes more common.

The research for the problem refinement process is based on the assumption that scientific researchers have needs to collaborate with others to solve their problems and develop the experiments tools and practices. It is also safe to assume that researchers meet issues in explicating the problems and need help from designers in these situations. This research simply suggests designers can implement this tool to help scientific researchers to refine the problems before and after the problem-solving process.

Assuming these points, researchers will understand that this study is to develop a guideline that will assist them in refining problems to develop experiments tools and practices. There will be a variety of directions that researchers can use to refine their problems. In design collaboration designers use these directions to help researchers refine problems and use this definition to collaborate with others to solve problems. Designers and researchers should understand that this is a tool for problem defining instead of problem solving.

1.6 Scope & Limits

This research, when applied to scientific researchers, should generate a guideline for designer collaborating with researchers towards the development of experimental tools and practices. The problem refinement tool is based on the logic of design, problem solving processes and past and present design methods. Additionally, the design methods may be limited to the areas that this thesis talks about. The approaches and strategies chosen by researchers should apply to scientific researchers and designers they collaborate with. Outcomes of definition may vary based on the researcher's own knowledge of the issues. The scope is also limited to knowledge of the researchers and designers who collaborate with each other. The scope of study is limited to the methods of design areas and the categories of sciences. The design methods may be limited to the areas that this thesis talks about.

This thesis involves collaboration between researchers and designers. In that case, it includes research on open innovation. The open innovation processes are limited to the areas that this thesis mentions about. The approach this thesis develops is based on open design process.

This research, when applied to scientific researchers, should generate an approach to direct problem-solving processes when problems happen during experiments and practices. The research only considers scientific researchers like PhD candidates and faculty in universities and research institutions. These people are professionals in their fields and willing to solve problems collaboratively. The problem-solving process is based on past and present design methods and the open innovation spirit. The study only focuses on procedures of experiments and practices based on ASTM International. The scope of this research is limited to the researchers from natural science. The scope is also limited to the numbers of departments in universities and research institutes.

The case discussed in this thesis, it lacks collaboration with engineers to develop. That may stimulate development the collaboration between researchers and designers.

1.7 Procedures and Methodology

The primary research method of this study is the literature review. The study will first review the logic of design, various types of design methods, open design processes and their characteristics. Furthermore, the study will review the past and present processes of problem-solving processes and mechanisms of collaboration and interdisciplinary work. In the second stage of this study, the logic of design is refined, and a problem refinement process is generated. The collaboration developing process is illustrated and the collaboration structure is developed. In the second stage of this study, the processes are demonstrated on a case from the NCAT (National for Asphalt Technology).

1.8 Anticipated Outcomes

It is anticipated that the outcome of this research will provide researchers with a synthesis of guidelines for refining problems from experiments and practices under designers' assistance. Problem refinement process for the researchers, as referred to in this research, is a tool created that allows direct problem definition. This tool should be designed and created by the designer to ensure the use of problem definition came from the researchers. This research will describe different strategies and methods toward developing problems refinement processes. This research will also show the outcome of developing experimental tools and practices by using this process.

Providing researchers with an understandable and user-friendly approach toward the direction for problem definition will help them to understand the purposes of problems and collaborate with designers easily. By encountering a problem, choosing a way to identify the initial problems and their extent, shrink the issues, and refine the problems, researchers will be able to figure out their situations regarding the issues in experiments and practices. This will provide researchers with designers' directions to input their actual need and problems to be solved.

This study will illustrate how to design a tool for problem refinement, using the guideline to develop tools from NCAT researchers' experiments.

Chapter 2: Literature Review

In order to develop an approach for problem solving process for scientific researchers based on design methods and open innovation, the literature review includes the study the logic of design, design methods, open innovation, problem solving processes, collaboration, interdisciplinarity and crossdisciplinarity.

2.1 Design Logic and Design Methods

Design has its unique logic. By analyzing the logic of design, we can understand the different reasoning methods designers and researchers use. Then the design methods are studied. The design methods offer the standard procedures which designers normally use. These methods can be applied in assisting scientific researchers' development of experimental tools and practices.

2.1.1 The Logic of Design

In order to figure out the logic of design, we need to study how many kinds of logic. There are three kinds of reasoning are Deduction, Induction and Abduction (Peirce, 1974).

In the 4th century BC, Aristotle started documenting deductive reasoning (Byrne, Evans, & Newstead, 1993). Deduction is one kind of reasoning which "examines the state of things asserted in the premisses, forms a diagram of that state of things, perceives in the parts of that diagram relations not explicitly mentioned in the premisses, satisfies itself by mental experiments upon the diagram that these relations would always subsist, or at least would do so in a certain proportion of cases, and concludes their necessary, or probable, truth" (Peirce, 1931, p. 28).

In the 300s BCE, Aristotle used the Greek word *epagogé*, which Cicero translated into the Latin word *inductio* (Gattei, 2009). Induction is one kind of reasoning which "adopts a conclusion as approximate, because it results from a method of inference which must generally lead to the truth in the long run.” (Peirce, 1931, p. 28)

Abduction, however, was also described as Retroduction by Pierce (1931). It is “the provisional adoption of a hypothesis, because every possible consequence of it is capable of experimental verification, so that the persevering application of the same method may be expected to reveal its disagreement with facts, if it does so disagree.” (p. 29)

After we talked about the categories of logics, we will focus on what kinds of logics designers use. Furthermore, we can compare the logic designers use to the logic which researchers use.

In the book, *Product Design: Fundamentals and Methods*, Roozenburg and Eekels (1995) mentioned Peirce’s three kinds of reasoning and built the core of design thinking on his work. In 2010, Dorst describes the basic reasoning patterns through comparing different ‘setting’ the unknowns and knowns in the equation in problem solving activity:

WHAT	**+**	**HOW**	leads to	**RESULT**
(thing)		(working principle)		(observed)

Equation 2.1 Problem Solving Equation (Dorst, 2011)

In Deduction, we know the ‘what’, which means we perceives the ‘thing’. We know ‘how’ the things will operate together. This allows us to conclude or predict results safely (Dorst, 2010). Deduction also is used for testing design solutions (Dorst, 2011).The equation shows as below:

WHAT + HOW leads to **???**

Equation 2.2 Deductive Reasoning Equation (Dorst, 2011)

Comparably, in Induction, we know the ‘what’ and we can observe results. But we do not know the ‘how’, which can explain (hypotheses) the results by perceiving the ‘thing’ (Dorst, 2010). The other equation shows this process:

WHAT + ??? leads to RESULT

Equation 2.3 Inductive Reasoning Equation (Dorst, 2011)

In the sciences, the discovery action is Deduction; the justification action is Induction. These two forms of actions help us to predict and explain the phenomena of the world (Dorst, 2010).

However, for productive thinking like design thinking, the equation changes a little: the attainment of a certain ‘value’ substitutes the ‘result’ (a statement of fact). We know what ‘value’ we want to achieve and ‘how’ the ‘working principle’ will help achieve the value (Dorst, 2011). The equation is:

WHAT	+	HOW	leads to	VALUE
(thing)		(working principle)		(aspired)

Equation 2.4 Productive Thinking Equation (Dorst, 2011)

Abduction is the basic reasoning pattern in productive thinking. The ‘what’ can present an object, a service, a system. Designers can use the working principle to work out the thing (the object, the service, the system). March (1984) also has taken abductive reasoning as the logic of design. In conventional problem solving, we usually know both the value we want to create and the ‘How’, a ‘working principle’ that will help we us achieve the value. The only thing missing is ‘what’, which is the definition of the problem and the potential solution space. This is often what designers and engineers do (Dorst, 2011). The equation is:

??? + HOW leads to VALUE

Equation 2.5 Abduction-1 Conventional Problem-solving Equation (Dorst, 2011)

However, in (conceptual) design, this equation looks like an ‘open’ form. The only thing we know is the end value we want to achieve. We do not know the ‘working principle’ and what to create (Dorst, 2011). The following equation, Abduction-2, can described the design activities mentioned by Roozenburg and Eekels (1995).

$$\underset{\text{(thing)}}{???} \quad + \quad \underset{\text{(working principle)}}{???} \quad \text{leads to} \quad \underset{\text{(aspired)}}{\text{VALUE}}$$

Equation 2.6 Abduction-2 (Conceptual) Design Problem-solving Equation (Dorst, 2011)

By coming up both a ‘thing’ and its ‘working principle’ that are linked to value, a ‘frame’ is the general implication that by applying a specific working principle we will create a specific value (Dorst, 2011). In creating new frame, the subtle process is related to phenomenological term called ‘theme’ (Van Manen, 1990). A ‘theme’ is experience of focus, of meaning. It is a sense-making tool, a form of capturing the underlying phenomenon one tries to understand.

$$\text{WHAT} \quad + \quad \underset{\text{——— FRAME ———}}{\text{HOW} \quad \text{leads to} \quad \text{VALUE}}$$

Equation 2.7 Different working principle lead to different ‘Value’ (Dorst, 2011)

This theory still has two issues to be solved. The first one is, without affecting the description of Dorst (2011), how to put the three reasoning skills in one equation because in that way we can talk about the differences between design and science activities in the same context. The second one is how to decide the ‘What’ to do and ‘How’ to do it if the ‘Value’ we want to create changes through productive thinking (in this thesis we just discuss design thinking).

The first issue can be explained by The Golden Circle, shows in Figure 2.1 on the left. From the outside, ‘WHAT’ stand for what we do. This is the behavior easy to identify. In the middle part is ‘HOW’ which means how we do what we do. HOWs are often given to explain how something is different or better. But they are not as obvious as WHATs. Inside the circle is ‘WHY’ represents why they do what they do. WHY means our purpose, cause and belief which helps us maintain innovation (Sinek, 2009). In Chapter 3.1 I give more specific description about the connection between The Golden Circle and Dorst theory. The Golden Circle corresponds to three major levels of the brain precisely. The neocortex is responsible for rational and analytical thought and language. The middle two sections are composed of the limbic brain which drives behavior and feeling, but it had no capacity for language. The behavior driven by the limbic brain may contradicts our rational and analytical understanding of a situation (Restak, 2006).

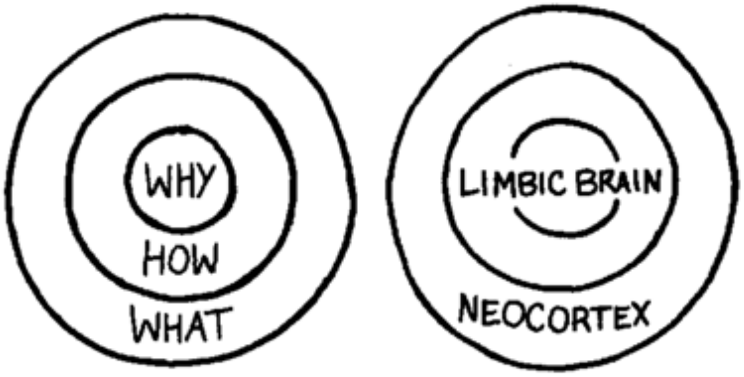


Figure 2.1 The Golden Circle (left) and the Brain Structure (right) (Sinek, 2009)

For companies, 'WHAT' they do and 'HOW' they do it are usually what customers asked for. But with the part of brain that controls decision making different from the part that controls rational and analytical thoughts (Sinek, 2009), 'WHY' needs to be dug up and recognized through designers' help.

Before talking about the second issue, Dorst (2011) mentioned the answer to how to create the value we are strive for is having the specific perception of a problem situation and adopt the working principle with that situation. Rittel (1984) also mentioned about the relation between understanding problem and the traits of designing: "you cannot understand the problem without having a concept of the solution in mind; and you cannot gather information meaningfully unless you have understood the problem but you cannot understand the problem without information about it" (p. 321). This dynamic change between the problem and the solution can be described as Recursion which is the inference of a case and partial rule from a result (Zeng & Cheng, 1991).

2.1.2 Design Methods and Design Processes

There are many design methods and processes developed by companies, organizations and councils. Analysis of similar and different characteristics from different design methods will lead to the attributes that will be used in the approach to help scientific researchers.

The Double Diamond

The double diamond describes the creative process shared by designers across disciplines. This visual map shows four stages of design process: discover, define, develop and deliver. The shape of the diamond represents divergent and convergent design process, which illustrate creating a number of possible ideas and then refining and narrowing down to the best idea. The word, “double” indicates that this process happens twice: the first one confirms the problem definition, and the second one creates the solution. The article mentions that omitting the left-hand diamond results in solving the wrong problem, which is one of the greatest mistakes.

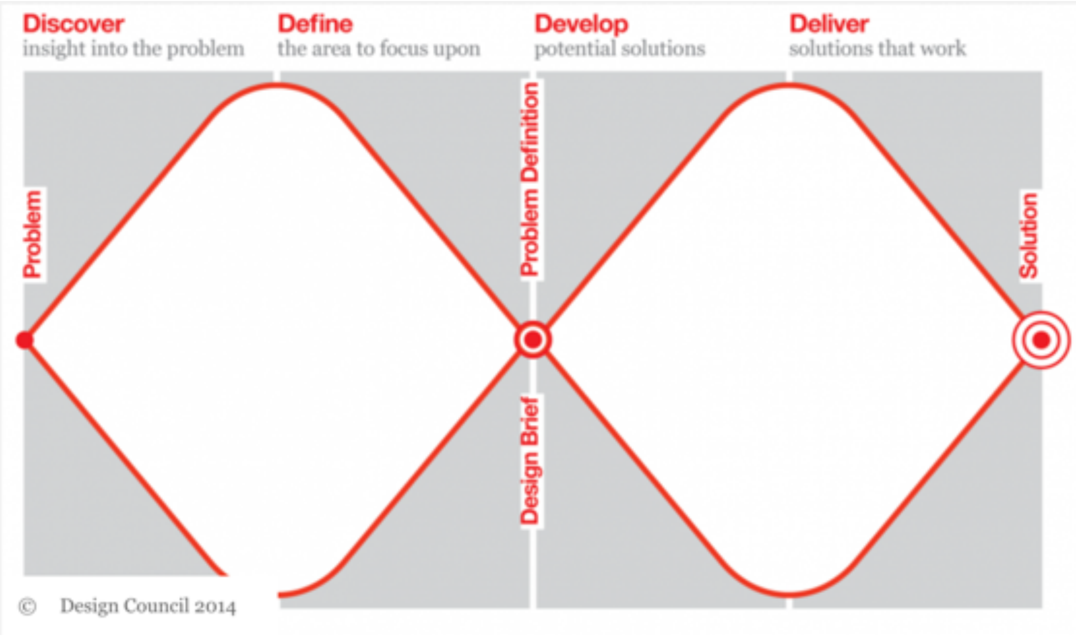


Figure 2.2 The Double Diamond (British Design Council)

The first diamond includes two phases: discover and define. The word “Discover” requires the designer to look at the work in a new way, notice fresh things and gather insights. The word “define” means looking for all the possibilities identified and developing a clear creative brief which can frame the fundamental design challenge (Design Council, 2015).

We can locate the problem when broadening the conceptual space discovered in the various scientific pursuits. In that way, we can begin to understand and express the nature of those differences (Mitchell, 2011).Instead of working toward a solution by searching for the central paradox, experienced designers tend to focus on issues around it and search the broader problem context for clues (Dorst, 2011).When researchers look for solutions, they already have a problem definition in their mind. However, it may not be the real problem, so this visual map (Figure 2.2) shows how important it is to discover the context of situation and redefine the problem.

In the book, *This is Service Design Thinking*, Stickdorn and Schneider (2010) discuss about this approach to the design of services. The authors illustrate that the service design process includes exploration, creation, reflection and implementation. The author also emphasizes that the service designer has sovereignty since co-creativity commonly occurs within the creative process. One of the tasks in the exploration phase is identifying the real problem, which includes gaining a clear understanding of the situation, keeping the big picture and ascertaining the real motivations behind customer behavior.

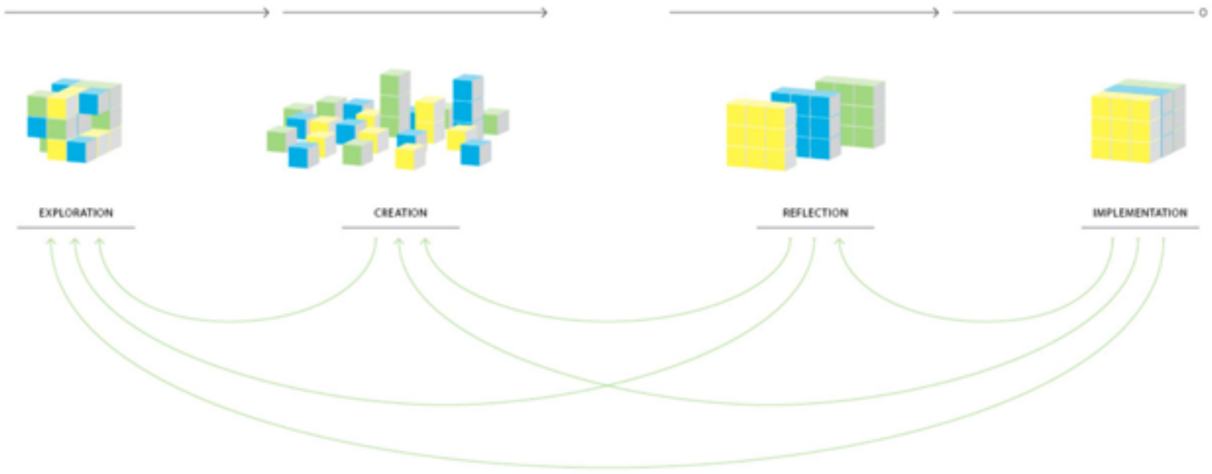


Figure 2.3 Service Design Iterative Development Process (Stickdorn & Schneider, 2010)

In the article named *Design Thinking: A Fruitful Concept for IT Development*, the authors state the double diamonds method in a more specific way as a context of IT development. The design thinking process breaks down to three characters: exploring the problem space, exploring the solution space and iterative alignment of both spaces. Learning about the problem is the first step of the design thinking process (Lindberg, Meinel, & Wagner, 2011).

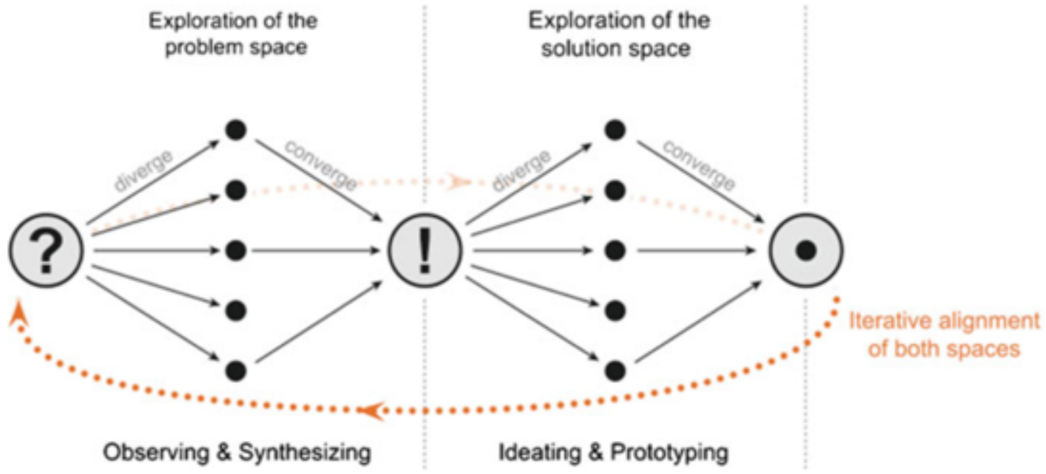


Figure 2.4 Problem and Solution Space in the Design Thinking (Lindberg, Meinel, & Wagner, 2011)

In *The Field Guide to Human-Centered Design*, a graphic states design thinking in a similar way as the previous books, but indicates that the divergent and convergent process. There are three phases: inspiration, ideation and implementation. After each diverge and converge process, designers will come closer and closer to a market-ready solution (IDEO.org, 2015).

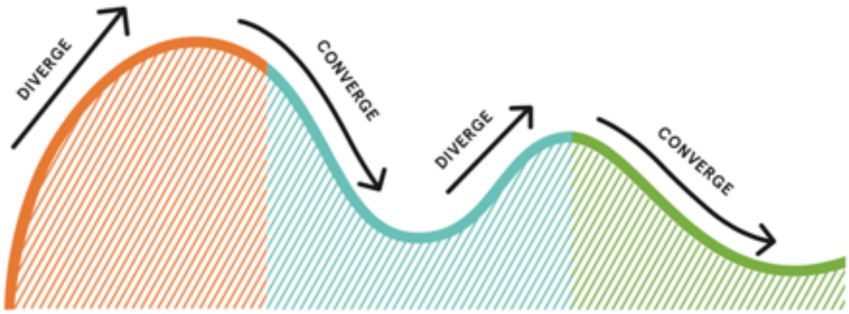


Figure 2.5 Diverge and Converge Along with Three Phases (Inspiration, Ideation and Implementation) (IDEO.org, 2015)

Furthermore, in *Design Thinking for Educators*, IDEO shows more details about this method. In the discovery phase, this process can be eye-opening. It is important to understand the challenge, prepare research and gather inspiration (IDEO, 2013).

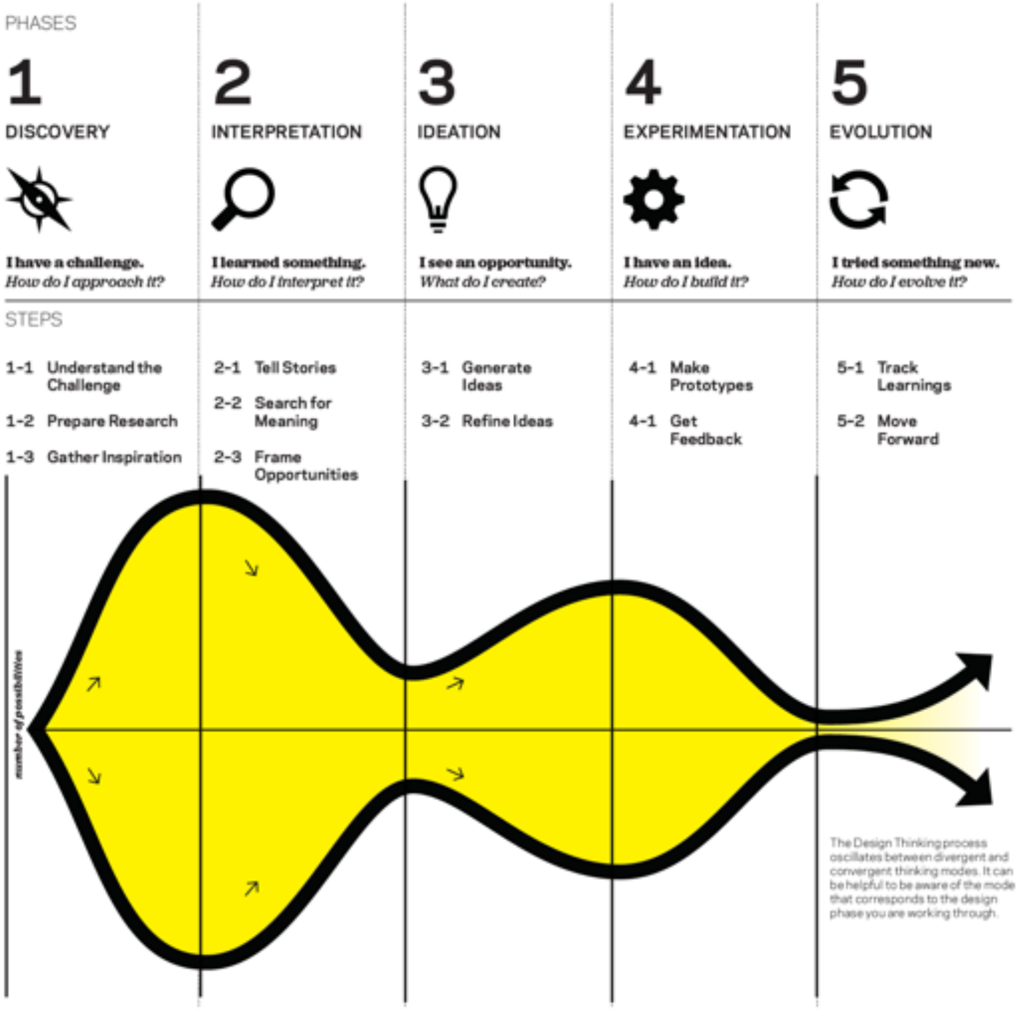
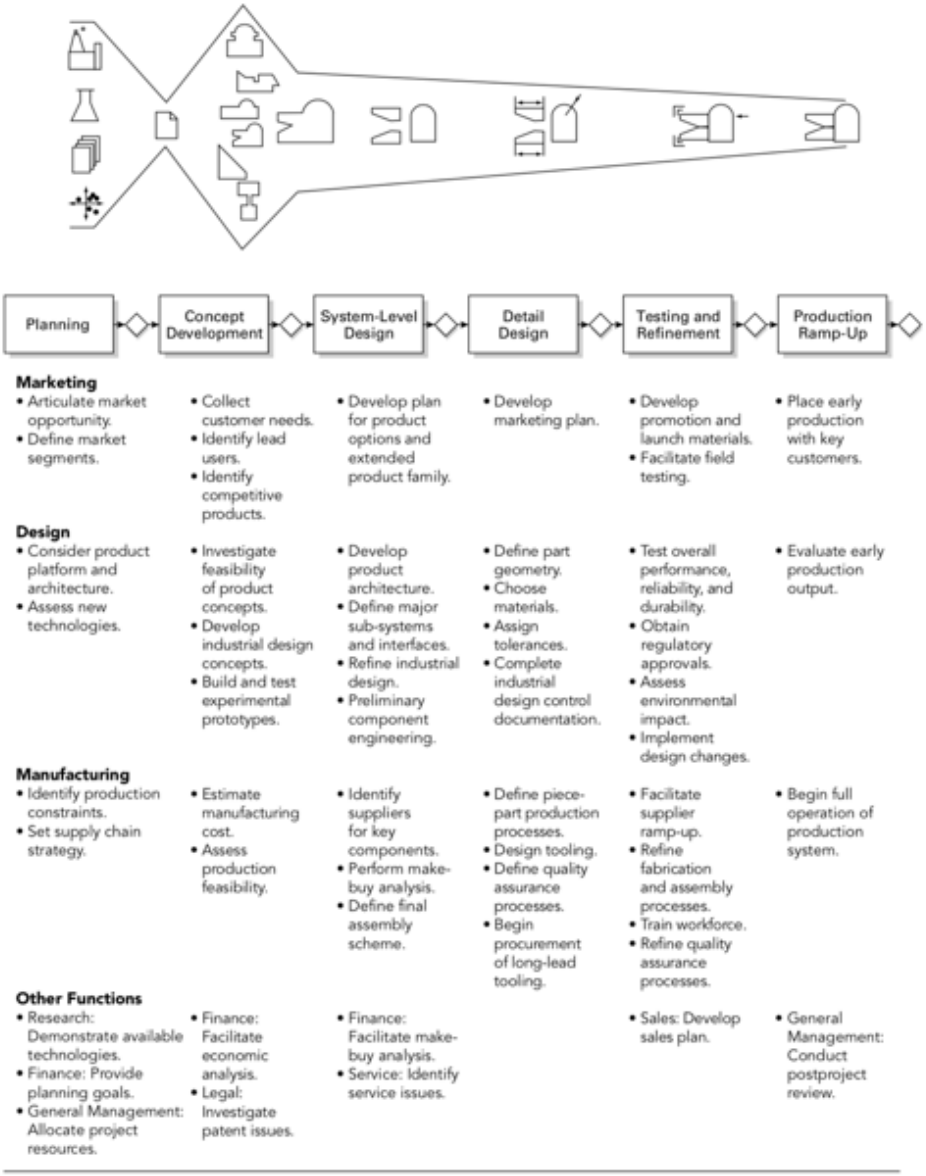


Table 2.1 IDEO Design Phases (IDEO, 2013)

In the book of *Product Design and Development (5th edition)*, Ulrich and Eppinger (2012) show about two converge processes including the planning process and the ideation process. The planning process is relatively simple because it eliminates the diverge process at the beginning of the design process. However, the second converge process requires more procedures than the methods I mentioned before. This converge process involves system-level design, detail design, testing and refinement and production ramp-up because of consideration of the consumer product development process. A well-defined development process will promote the quality of assurance, coordination, planning, management and improvement.



	Planning	Concept Development	System-Level Design	Detail Design	Testing and Refinement	Production Ramp-Up
Marketing	• Articulate market opportunity. • Define market segments.	• Collect customer needs. • Identify lead users. • Identify competitive products.	• Develop plan for product options and extended product family.	• Develop marketing plan.	• Develop promotion and launch materials. • Facilitate field testing.	• Place early production with key customers.
Design	• Consider product platform and architecture. • Assess new technologies.	• Investigate feasibility of product concepts. • Develop industrial design concepts. • Build and test experimental prototypes.	• Develop product architecture. • Define major sub-systems and interfaces. • Refine industrial design. • Preliminary component engineering.	• Define part geometry. • Choose materials. • Assign tolerances. • Complete industrial design control documentation.	• Test overall performance, reliability, and durability. • Obtain regulatory approvals. • Assess environmental impact. • Implement design changes.	• Evaluate early production output.
Manufacturing	• Identify production constraints. • Set supply chain strategy.	• Estimate manufacturing cost. • Assess production feasibility.	• Identify suppliers for key components. • Perform make-buy analysis. • Define final assembly scheme.	• Define piece-part production processes. • Design tooling. • Define quality assurance processes. • Begin procurement of long-lead tooling.	• Facilitate supplier ramp-up. • Refine fabrication and assembly processes. • Train workforce. • Refine quality assurance processes.	• Begin full operation of production system.
Other Functions	• Research: Demonstrate available technologies. • Finance: Provide planning goals. • General Management: Allocate project resources.	• Finance: Facilitate economic analysis. • Legal: Investigate patent issues.	• Finance: Facilitate make-buy analysis. • Service: Identify service issues.		• Sales: Develop sales plan.	• General Management: Conduct postproject review.

Table 2.2 The Generic Product Development Process (Ulrich & Eppinger, 2012)

In 2010, the book of Stanford's d.school, *An Introduction to Design Thinking Process*

Guide (Plattner, 2010), offer a design process which is popular. However, this process is simplified to five steps including empathize, define, ideate, prototype and test. It is a linear process which offers a general guideline for designers and non-designers.

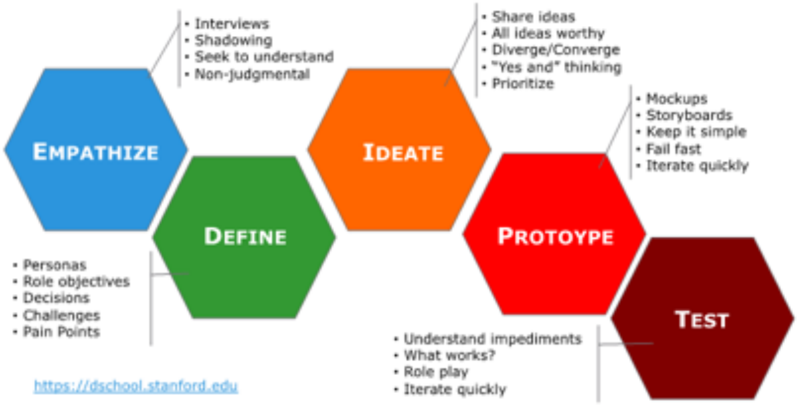


Figure 2.6 Design Thinking Process from Stanford's d.school

Graphic from https://medium.com/@sts_news/the-design-thinking-movement-is-absurd-83df815b92ea

In the book, *Sprint: How to Solve Big Problems and Test New Ideas in Just Five Days*, the authors also offer a linear guide to design. This process offers a more specific DIY guide to answer pressing business questions. This process aimed at offering "startups a superpower" and " Identifying critical flaws after just five days of work is the height of efficiency" (Knapp, Zeratsky, & Kowitz, 2016, p. 16). This compact procedure may benefit researchers who need to save time.

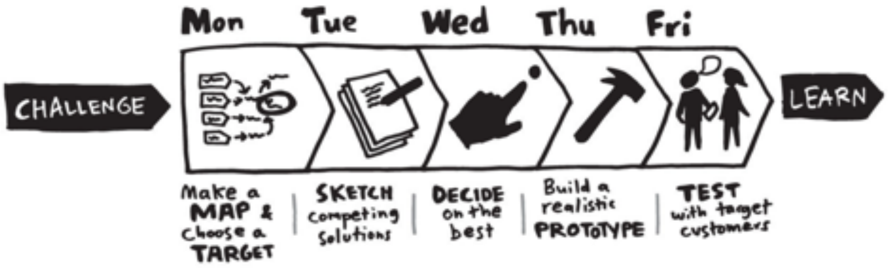


Figure 2.7 Sprint Design Process (Knapp, Zeratsky, & Kowitz, 2016)

According to Gibbons (2016), the design thinking framework follows a flow:

understanding, explore and materialize. Within these buckets, there are six phases: empathize, define, ideate, prototype, test and implement. The circle shape means continuously improving. In the problem-solving process, the context of problem can change along with the new condition. In that case the definition of the problem is never really definitive and can always improve.

Figure 2.8 Design Thinking Process from Gibbons (2016)

2.2 Problem Solving Process

In order to offer an approach to solve the problems, the problem-solving process needs to be researched. Problems show up when there is need from people who are motivated to search for a solution to eliminate discrepancies (Arlin, 1989).

The problem-solving process relies on the problem solver’s understanding and representation of the problem state and goal state. A set of operators known as problem space and problem schema (Wood, 1983) need to be defined in order to move from the initial state to the goal state. The problem space is "the fundamental organizational unit of all human goal-activity" (Newell, 1980, p. 696).

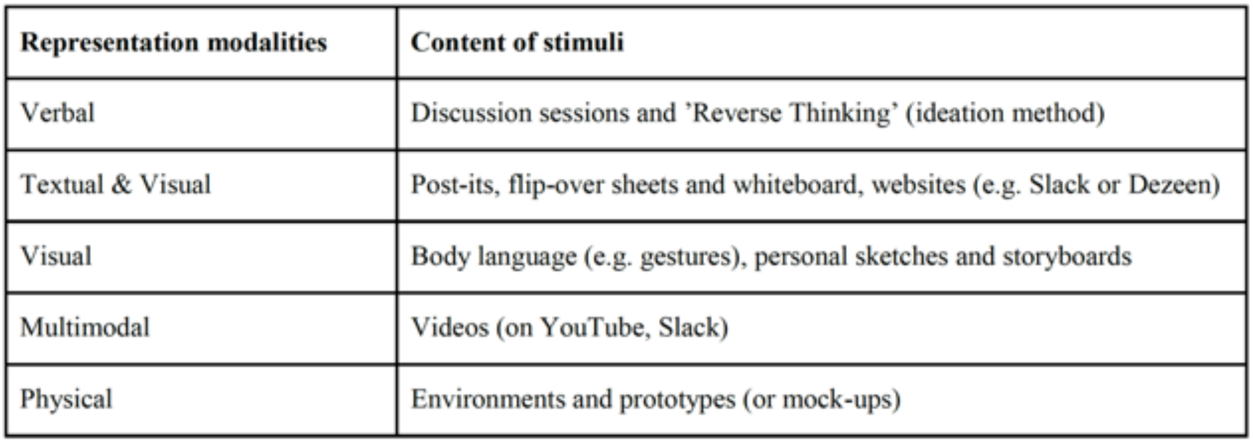
2.2.1 Problem Classification

There are three kinds of problems: puzzle problems, well-structured problems and ill-structured problems. Puzzle problems are well-structured and have a single correct solution where all elements required for the solution are known (Kitchner, 1983). Well-structured problems, however, require the application of a finite number of concepts, rules and principles being studied. Ill-structured problems contain opposite or contradictory evidence. Their solutions are not predictable or convergent (Jonassen, 2000). There is not a single, correct solution that can be determined through a specific decision-making process (Kitchner, 1983).

2.2.2 Problem-solving Process

In the problem-solving process, the first step is problem definition. There are three factors that impact design problem definition: the co-creation session setup and structure, cultural perceptions and norms, and interpretation of the user data (Dastmalchi, 2017).

Additionally, Dankfort, Roos, and Goncalves (2018) propose five main purposes of stimuli to inspire the design team and other members, to explain their ideas to team members, and test the assumptions when they figure out problems and solutions collaboratively.



Representation modalities	**Content of stimuli**
Verbal	Discussion sessions and 'Reverse Thinking' (ideation method)
Textual & Visual	Post-its, flip-over sheets and whiteboard, websites (e.g. Slack or Dezeen)
Visual	Body language (e.g. gestures), personal sketches and storyboards
Multimodal	Videos (on YouTube, Slack)
Physical	Environments and prototypes (or mock-ups)

Table 2.3 Types of Stimuli Representation Modalities and Content (Dankfort, Roos, & Gonçalves, 2018)

These five types of stimuli enable the design process to work more smoothly than when using only verbal communication. The problem and solution space can continuously iterate to build better understanding and trigger inspirations.

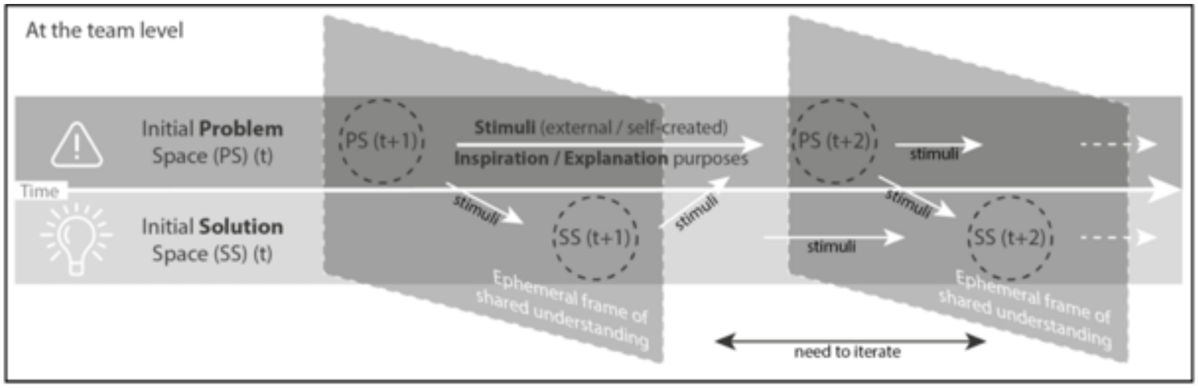


Figure 2.9 How the Use of Stimuli Leads to More Inspiration and Possibly More Creativity (Dankfort, Roos, & Gonçalves, 2018)

Scholz (2001) mentioned that the method of knowledge begins from understanding by empathy, feeling, pictorial representation and comprehension to organizing knowledge based on problem representation, problem evaluation and problem transition.

Gick (1986) developed a simplified schematic of the well-structured problem solving process. This process will continue by presenting the problem and generating alternative solutions until a successful solution is found. However, this schematic does not emphasize finding more than one solution that will work.

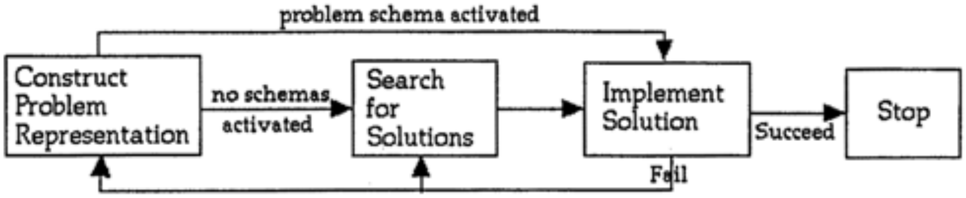


Figure 2.10 Simplified Schematic of Problem-solving Process (Gick, 1986)

In order to explicate the complexity of well-structured problem solving process, Jonassen (1997) developed a process that involves mapping the problem statement onto prior knowledge, problem decomposition (find sub-goals), and means-ends analysis. The function of means-ends analysis is reducing the discrepancy between the current state and the goal statement of the problem (Gick, 1986).

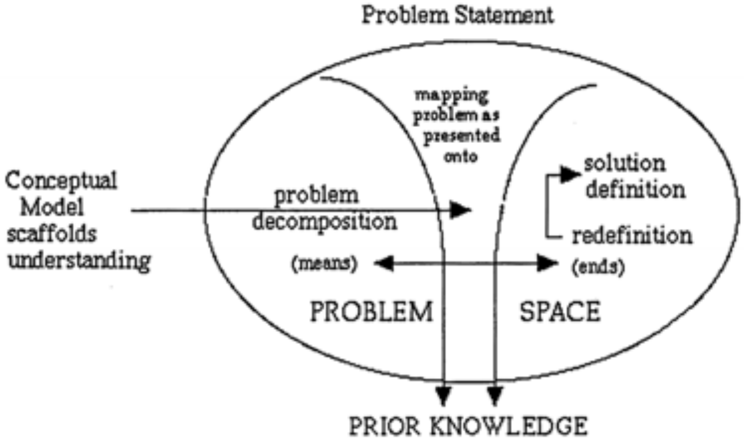
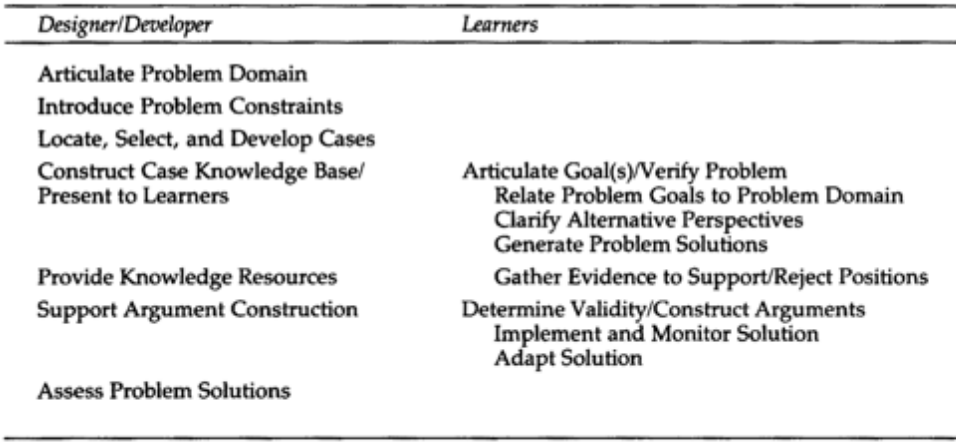


Figure 2.11 Conceptual Model of the Well-structured Problem-solving Process (Gick, 1986)

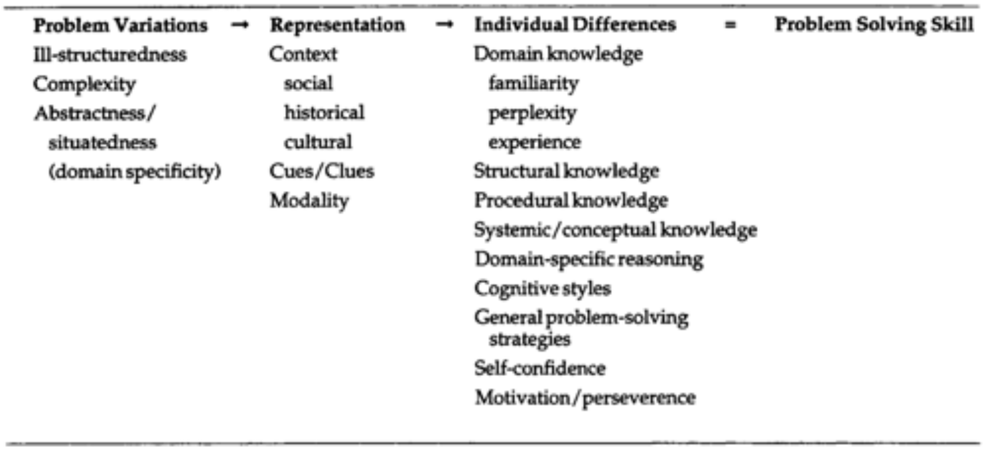
For ill-structured problem-solving, the designer must collaborate with subject matter experts and experienced practitioners to accomplish tasks. Those tasks include articulating the problem context; introducing problem constraints: locating, selecting and developing cases, supporting knowledge base construction supporting argument construction; and assessing problem solutions. Solving ill-structured problem is an iterative and cyclical process (Jonassen, 1997).



Designer/Developer	*Learners*
Articulate Problem Domain	
Introduce Problem Constraints	
Locate, Select, and Develop Cases	
Construct Case Knowledge Base/ Present to Learners	Articulate Goal(s)/Verify Problem Relate Problem Goals to Problem Domain Clarify Alternative Perspectives Generate Problem Solutions
Provide Knowledge Resources	Gather Evidence to Support/Reject Positions
Support Argument Construction	Determine Validity/Construct Arguments Implement and Monitor Solution Adapt Solution
Assess Problem Solutions	

Table 2.4 Implementation Process for Ill-structured Problems (Jonassen, 1997)

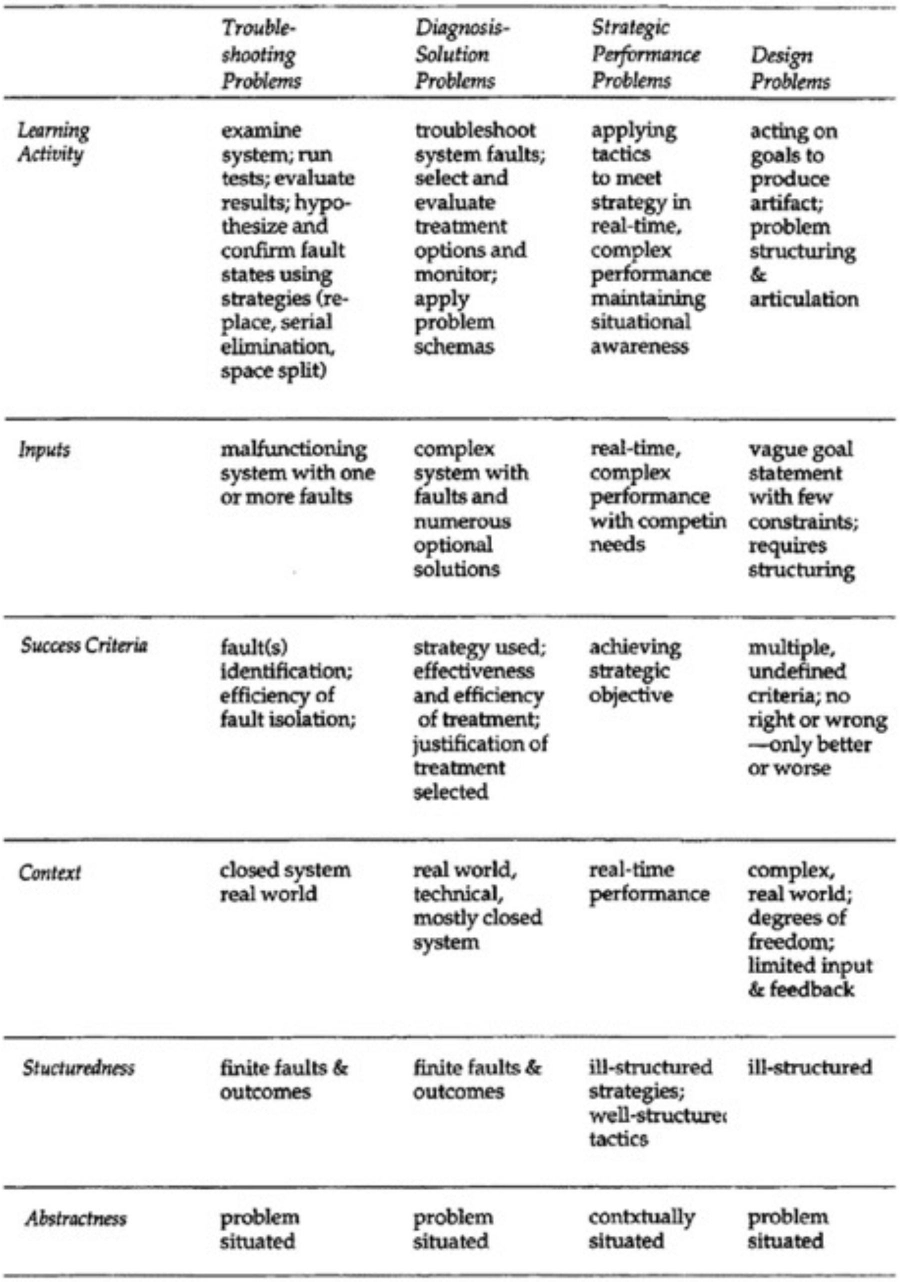
Jonassen (2000) believed that “the ability to solve problems is a function of the nature of the problem (problem variation), the way that the problem is represented to the solver, and a host of individual differences that mediate the process” (p. 66). He also described differences among problems including structuredness, complexity and abstractness(Jonassen, 2000). Problem complexity is defined by the number of issues, variables; the functions involved in the problem; the degree of connectivity, the type of function relationships and the stability among those properties (Funke, 1991). He also mentioned about a variety of individual differences that affect problem solving (Jonassen, 2000).



Problem Variations →	**Representation** →	**Individual Differences** =	**Problem Solving Skill**
Ill-structuredness	Context	Domain knowledge	
Complexity	social	familiarity	
Abstractness/	historical	perplexity	
situatedness	cultural	experience	
(domain specificity)	Cues/Clues	Structural knowledge	
	Modality	Procedural knowledge	
		Systemic/conceptual knowledge	
		Domain-specific reasoning	
		Cognitive styles	
		General problem-solving strategies	
		Self-confidence	
		Motivation/perseverence	

Figure 2.12 Problem-solving Skills (Jonassen, 2000)

Based on the typology of problems Jonassen (2000) articulated, there are four types of problems this thesis will be concerned with: trouble-shooting problems, diagnosis-solution problems, strategic performance problems and design problems. Those problems engage different learning activities, inputs, success criteria, context, structuredness and abstractness. Those are types of problems we discuss in assisting researchers.



	Trouble-shooting Problems	*Diagnosis-Solution Problems*	*Strategic Performance Problems*	*Design Problems*
Learning Activity	examine system; run tests; evaluate results; hypothesize and confirm fault states using strategies (replace, serial elimination, space split)	troubleshoot system faults; select and evaluate treatment options and monitor; apply problem schemas	applying tactics to meet strategy in real-time, complex performance maintaining situational awareness	acting on goals to produce artifact; problem structuring & articulation
Inputs	malfunctioning system with one or more faults	complex system with faults and numerous optional solutions	real-time, complex performance with competin needs	vague goal statement with few constraints; requires structuring
Success Criteria	fault(s) identification; efficiency of fault isolation;	strategy used; effectiveness and efficiency of treatment; justification of treatment selected	achieving strategic objective	multiple, undefined criteria; no right or wrong —only better or worse
Context	closed system real world	real world, technical, mostly closed system	real-time performance	complex, real world; degrees of freedom; limited input & feedback
Stucturedness	finite faults & outcomes	finite faults & outcomes	ill-structured strategies; well-structure tactics	ill-structured
Abstractness	problem situated	problem situated	contxtually situated	problem situated

Table 2.5 A Description of Four Problem Types (Trouble-shooting Problems, Diagnosis-solution Problems, Strategic Performance Problems and Design Problems) (Jonassen, 2000)

2.3 Open Design

2.3.1 Open Design Definition

The three main elements of product design are "First, the input of the process (that is, the gap); then, the process itself (described through the phases and activities it consists of, the boundary objects used, and the stakeholders involved); and, lastly, the output of this process (that is, the plan)" (Boisseau et al., 2018, p. 5). The relationship can be described by the graphic from *Design: Creation of Artifacts in Society* (Ulrich, 2011).

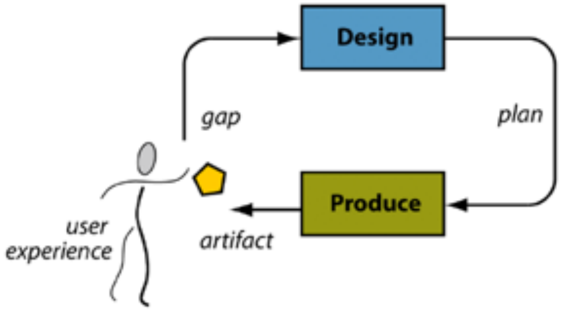
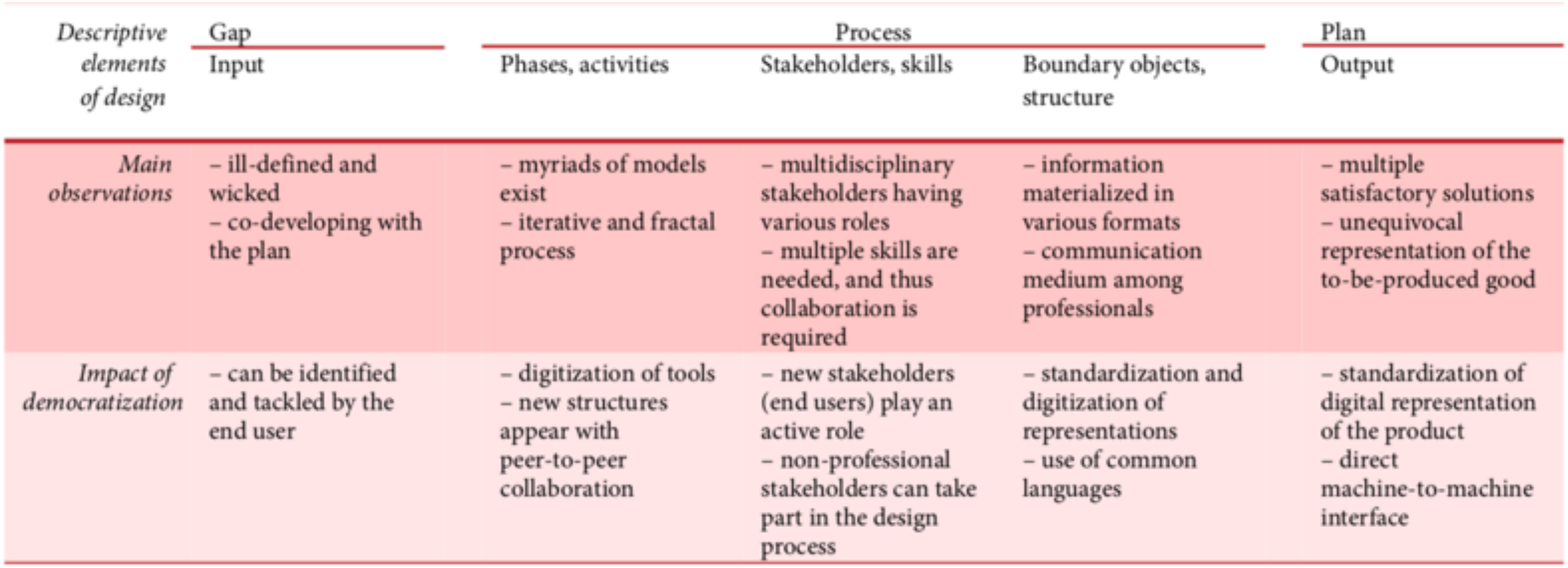


Figure 2.13 Design and Production Are the Two Activities that Deliver Artifacts to Address Gaps in the User Experience (Ulrich, 2011)

Openness will affect the design process in all three elements: gap, process and plan (Boisseau et al., 2018). The same as the graphic illustrated above, according to Rittel and Webber (1973), the problem identification also should narrow the gap between what-is and what-ought-to-be.



Descriptive elements of design	Gap	Process			Plan
	Input	Phases, activities	Stakeholders, skills	Boundary objects, structure	Output
Main observations	– ill-defined and wicked – co-developing with the plan	– myriads of models exist – iterative and fractal process	– multidisciplinary stakeholders having various roles – multiple skills are needed, and thus collaboration is required	– information materialized in various formats – communication medium among professionals	– multiple satisfactory solutions – unequivocal representation of the to-be-produced good
Impact of democratization	– can be identified and tackled by the end user	– digitization of tools – new structures appear with peer-to-peer collaboration	– new stakeholders (end users) play an active role – non-professional stakeholders can take part in the design process	– standardization and digitization of representations – use of common languages	– standardization of digital representation of the product – direct machine-to-machine interface

Table 2.6 Major Features of the Design Process and Its Democratization (Boisseau et al., 2018)

Based on the two dimensions of process and plan, the relation between open design and open innovation can be described by the graphic (Boisseau et al., 2018) below. We can see that open design and open innovation both have relatively open processes. We can discuss processes of open design and open innovation in the same context without considering the level of plan opening.

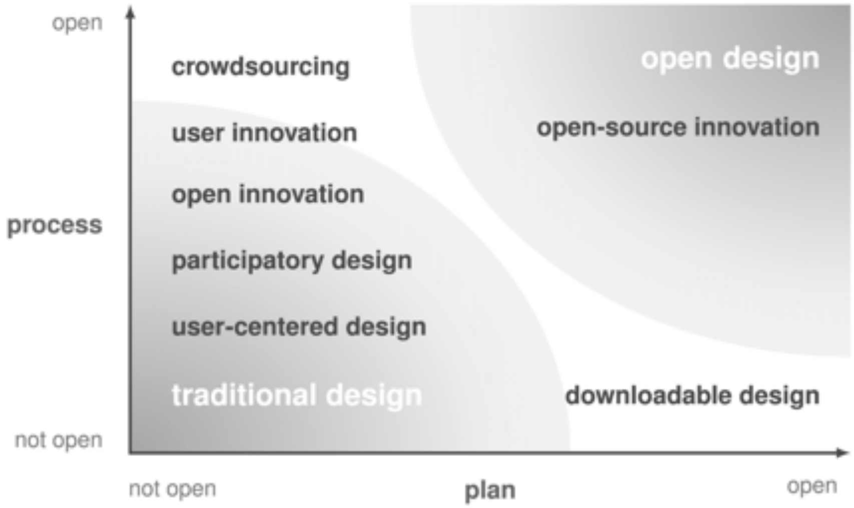


Figure 2.14 Open-design and Related Concepts (Boisseau et al., 2018)

In open design, roles of the stakeholders change and blur according to Stappers, Visser, and Kistemaker (2011). Three roles (users, designers and producers) and responsibilities are “interacting, merging, or even being swapped back and forth between parties; so, roles are disappearing in the form in which we knew them, and new roles are appearing” (p. 143) Like these authors said, in this thesis’s context, the scientific researchers’ role can change from user to designer or producer.

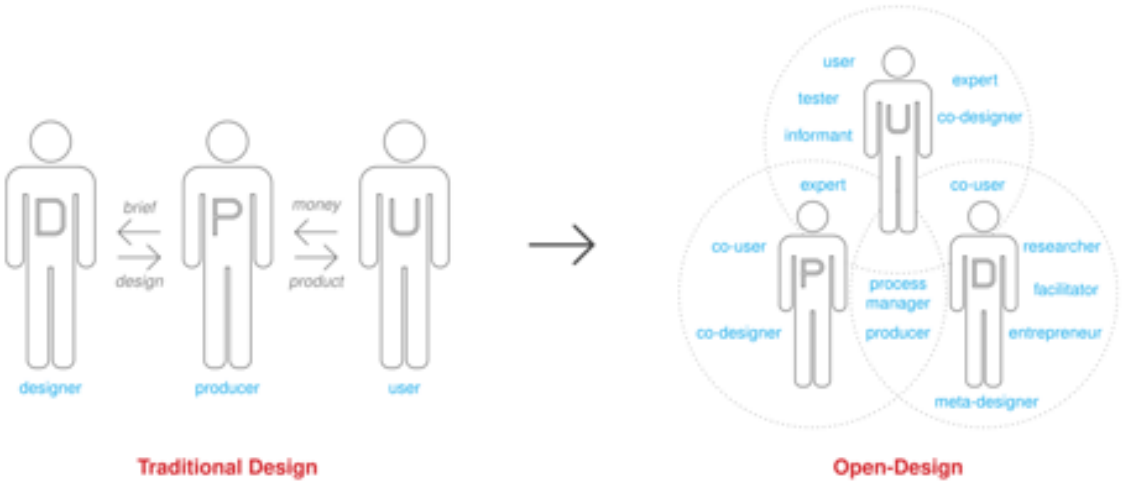


Figure 2.15 Open-Design Compare to Tradition Design (Stappers, Visser, & Kistemaker, 2011)

2.3.2 Open Design Process

In an article "The Open Paradigm in Design Research" (Aitamurto et al., 2015), the definition of open design is:

"The open design process provides public access to participation in the design process and to the product resulting from that process, as well as the data created in the design process, including technical details and other data and content gathered or generated during the process." (p. 22)

This definition of "open design includes all stages in the design process, from need-finding to ideation, and in the production process, intertwining the aspects of technical, legal, and commercial openness" (Aitamurto et al., 2015, p. 22) This is shown in the Figure 2.16 .

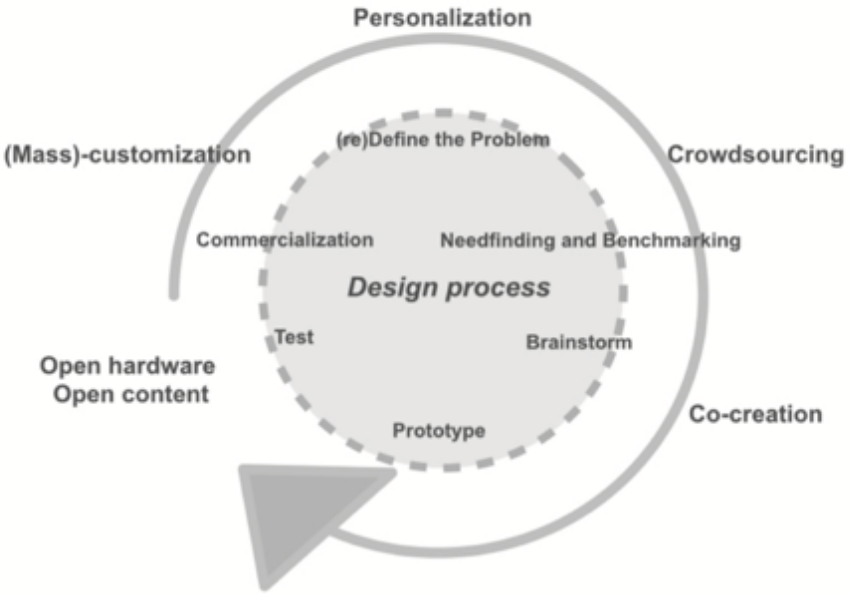
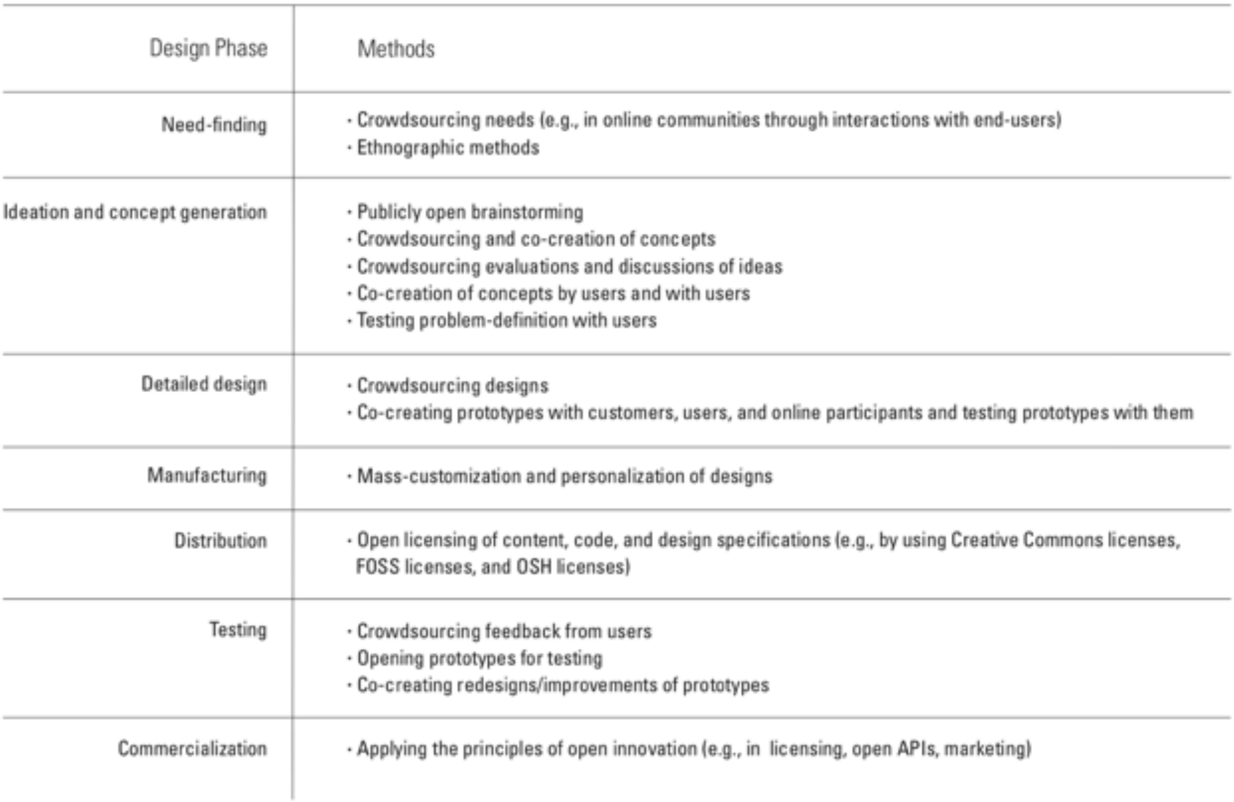


Figure 2.16 Open Design Practices and Design Process (Aitamurto et al., 2015)

2.3.3 Open Design Practices

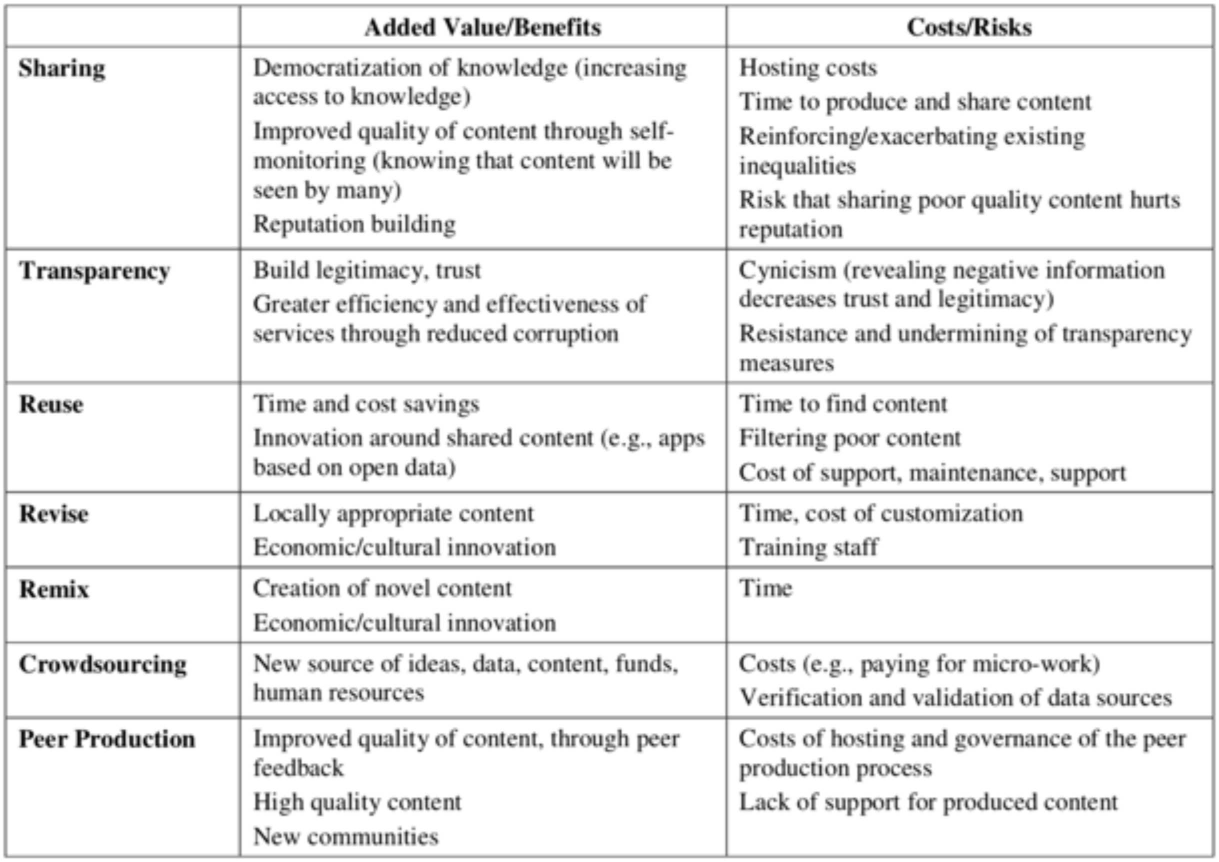
Open design practices have the potential to benefit to the design process. More solutions can be used in the design process like crowdsourcing and co-creation than in closed processes (Aitamurto et al., 2015). In this way, scientific researchers potentially will receive more useful solutions.



Design Phase	Methods
Need-finding	· Crowdsourcing needs (e.g., in online communities through interactions with end-users) · Ethnographic methods
Ideation and concept generation	· Publicly open brainstorming · Crowdsourcing and co-creation of concepts · Crowdsourcing evaluations and discussions of ideas · Co-creation of concepts by users and with users · Testing problem-definition with users
Detailed design	· Crowdsourcing designs · Co-creating prototypes with customers, users, and online participants and testing prototypes with them
Manufacturing	· Mass-customization and personalization of designs
Distribution	· Open licensing of content, code, and design specifications (e.g., by using Creative Commons licenses, FOSS licenses, and OSH licenses)
Testing	· Crowdsourcing feedback from users · Opening prototypes for testing · Co-creating redesigns/improvements of prototypes
Commercialization	· Applying the principles of open innovation (e.g., in licensing, open APIs, marketing)

Table 2.7 Openness in the Design Process (Aitamurto et al., 2015)

Along with the improvement of the information and communication technology, we can easily access to the internet anywhere and anytime (Smith, 2014). In this context, the meaning of openness in Information and Communication Technology for Development (ICT4D) can be defined as “openness provides the possibility for a set of practices (open practices) that we theorize can help to achieve development benefits” (Smith, 2014, pp. 5-6). The open practices have potential to benefit researchers. That makes openness important to researchers. There are at least seven open practices including sharing, transparency, reuse, revising, remixing, crowdsourcing and peer production. Based on ASTM International, those seven practices can benefit solving the problems scientific researchers meet in experiments and practices. Each of the seven openness practices include the value added and costs engaging:



	Added Value/Benefits	Costs/Risks
Sharing	Democratization of knowledge (increasing access to knowledge) Improved quality of content through self-monitoring (knowing that content will be seen by many) Reputation building	Hosting costs Time to produce and share content Reinforcing/exacerbating existing inequalities Risk that sharing poor quality content hurts reputation
Transparency	Build legitimacy, trust Greater efficiency and effectiveness of services through reduced corruption	Cynicism (revealing negative information decreases trust and legitimacy) Resistance and undermining of transparency measures
Reuse	Time and cost savings Innovation around shared content (e.g., apps based on open data)	Time to find content Filtering poor content Cost of support, maintenance, support
Revise	Locally appropriate content Economic/cultural innovation	Time, cost of customization Training staff
Remix	Creation of novel content Economic/cultural innovation	Time
Crowdsourcing	New source of ideas, data, content, funds, human resources	Costs (e.g., paying for micro-work) Verification and validation of data sources
Peer Production	Improved quality of content, through peer feedback High quality content New communities	Costs of hosting and governance of the peer production process Lack of support for produced content

Table 2.8 Example Value Added and Costs of Engaging in the 7 Open Practices (Smith, 2014)

The approach this thesis develops should focus on maximizing added value and minimizing the cost of the experimental tools and practices for the scientific researchers from openness practices. The approach developed in this thesis also aims at increasing value and reducing the cost for scientific researchers.

2.3.4 Case Study of Open Design

OpenIDEO (https://www.openideo.com/) is a platform identified as the core operating principle of online collaboration. It offers six phases: ideas, feedback, refinement, evaluation, top ideas, impact (Micklethwaite, 2017). OpenIDEO requires problem-solvers to answer specific questions to explain the solutions including concept title, concept, how it works etc. Considering what is the ultimate delivery of solutions is important for the tool offered in this thesis.

2.4 Research Collaboration

2.4.1 Problem Solving Collaboration Skill

Hesse et al. (2015) proposed a framework that breaks down collaborative problem-solving skills into two very broad skill classes: social skills and cognitive skills. Social skills help individuals coordinate actions in synchrony with other participants. In addition, these social skills can be divided to three aspects: participation, perspective thinking, and social regulation. Participation describes the minimum requirements for collaborative interaction. The concept of perspective taking skills refers to the ability to see a problem through the eyes of a collaborator (cited in Higgins, 1981). Social regulation skills mean the strategic aspects of collaborative problem solving (Peterson, 2005). Authors categorize three levels of collaboration: low, middle, high (Hesse, Care, Buder, Sassenberg, & Griffin, 2015).

2.4.2 Research Collaboration

Bozeman, Gaughan, Youtie, Slade, and Rimes (2016) offer a model of research collaboration effectiveness This model includes three constructs: external factors, team characteristics, individual team members, and team management. A variety of factors influence the effectiveness of research collaboration.

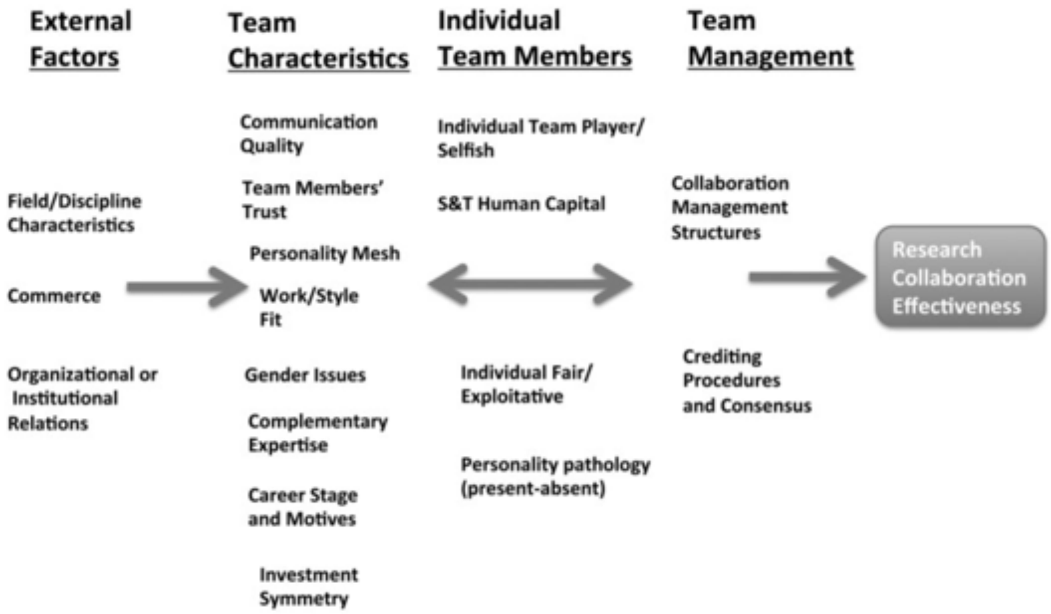


Figure 2.17 Model of Research Collaboration Effectiveness (Bozeman, Gaughan, Youtie, Slade, & Rimes, 2016)

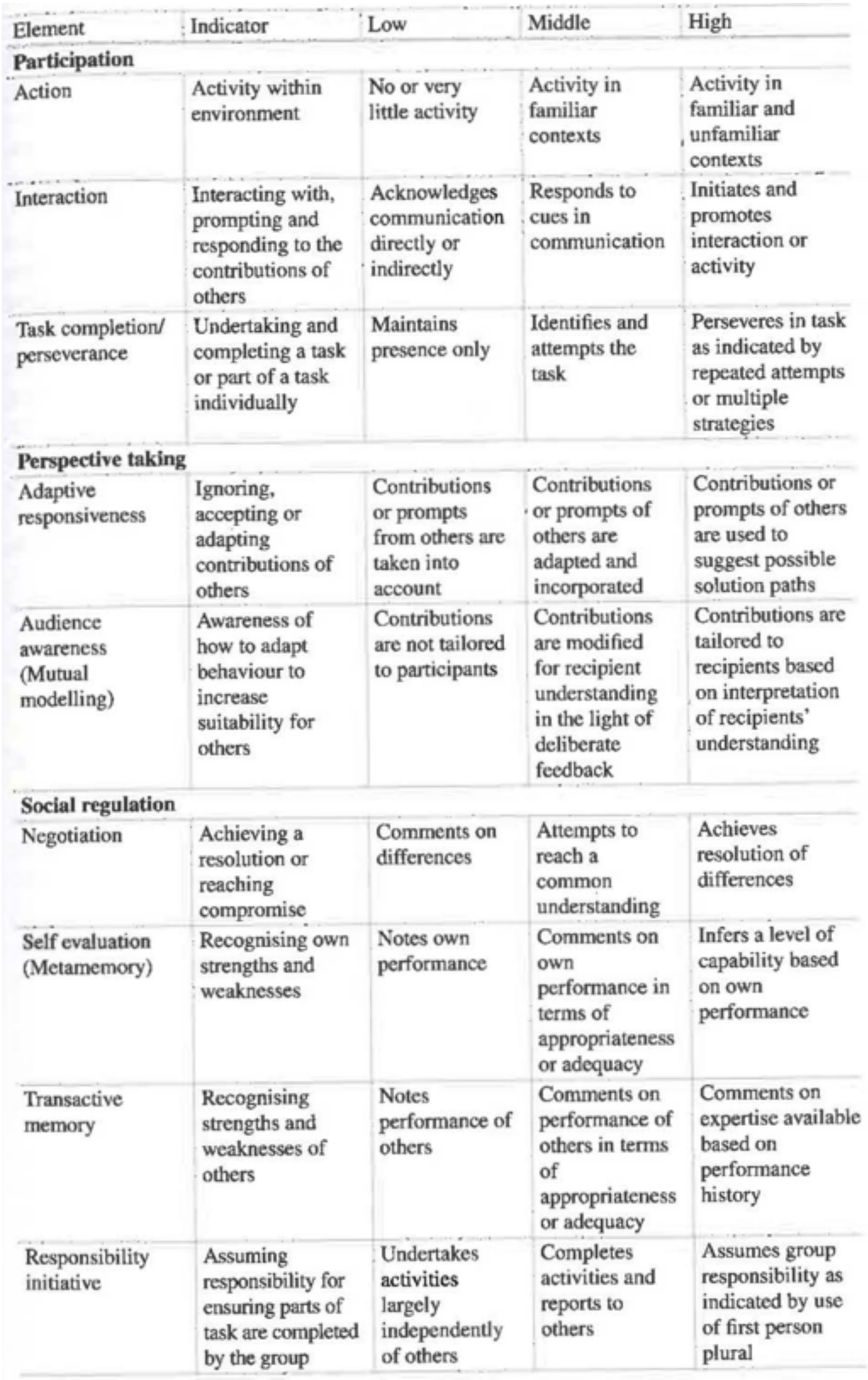
Daniel Stokols (2006) stated about the attributes about the scientific collaborations:

> "Collaborations among researchers and community practitioners diverge from purely scientific collaborations in several respects. First, the intended outcomes of researcher-practitioner partnerships are the translation of scientific findings into community problem solving strategies such as health promotion programs and policies, and the promotion of social justice and community well-being. … Second, collaborations among researchers and community practitioners must bridge not only diverse scientific fields but also a variety of professional and lay perspectives. Third, scientific collaborations tend to be university-centric—that is, the environmental contexts of those collaborations are usually university or research institute offices and laboratories" (p. 69).

Additionally, collaboration is highly related to geography. Scientists are more likely to collaborate if their working places are located within the same region. The more often two scientists attend the conference together, they are more likely to collaborate. However, in order to focus on individual performance that is measured for tenure and promotion, scientists tend to avoid cross-organization collaboration (Binz-Scharf et al., 2015). In this thesis, by assisting researchers develop experimental tools and practices, designers can improve the efficiency of daily work of researchers which promote individual performance.

2.4.3 Crowd Research

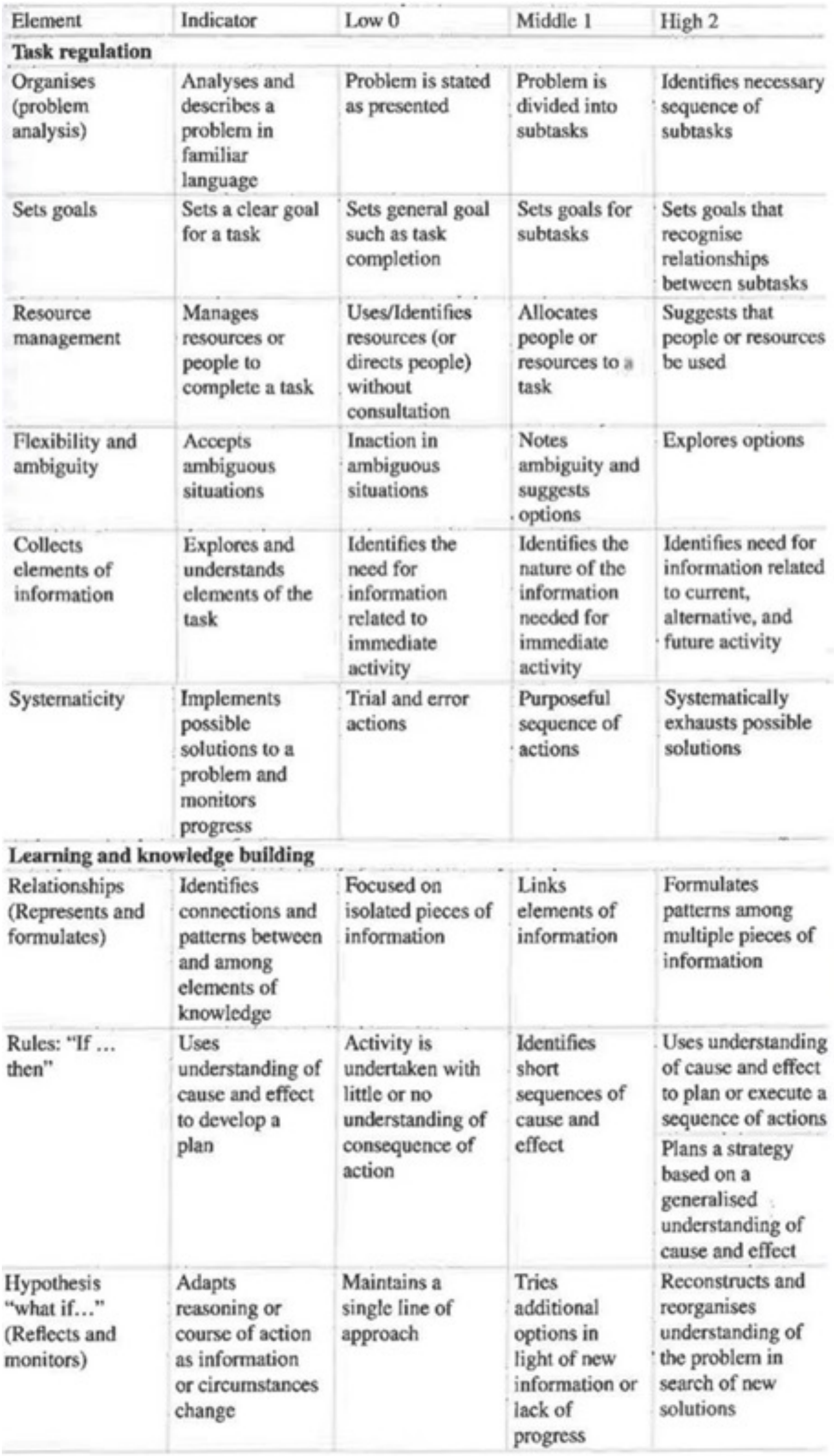
Crowd Research is a crowdsourcing technique which enables open access for global crowds to work together on research under a principal investigator. Participants can build real-world systems and co-authored papers by utilizing crowd research (Meinel, 2019). Crowd research needs social skills and cognitive skills in collaborative problem solving. Social skills contain participation, perspective taking and social regulation. Hesse et al. (2015) categorize to three levels of collaboration: low, middle, high.



Element	Indicator	Low	Middle	High
Participation				
Action	Activity within environment	No or very little activity	Activity in familiar contexts	Activity in familiar and unfamiliar contexts
Interaction	Interacting with, prompting and responding to the contributions of others	Acknowledges communication directly or indirectly	Responds to cues in communication	Initiates and promotes interaction or activity
Task completion/ perseverance	Undertaking and completing a task or part of a task individually	Maintains presence only	Identifies and attempts the task	Perseveres in task as indicated by repeated attempts or multiple strategies
Perspective taking				
Adaptive responsiveness	Ignoring, accepting or adapting contributions of others	Contributions or prompts from others are taken into account	Contributions or prompts of others are adapted and incorporated	Contributions or prompts of others are used to suggest possible solution paths
Audience awareness (Mutual modelling)	Awareness of how to adapt behaviour to increase suitability for others	Contributions are not tailored to participants	Contributions are modified for recipient understanding in the light of deliberate feedback	Contributions are tailored to recipients based on interpretation of recipients' understanding
Social regulation				
Negotiation	Achieving a resolution or reaching compromise	Comments on differences	Attempts to reach a common understanding	Achieves resolution of differences
Self evaluation (Metamemory)	Recognising own strengths and weaknesses	Notes own performance	Comments on own performance in terms of appropriateness or adequacy	Infers a level of capability based on own performance
Transactive memory	Recognising strengths and weaknesses of others	Notes performance of others	Comments on performance of others in terms of appropriateness or adequacy	Comments on expertise available based on performance history
Responsibility initiative	Assuming responsibility for ensuring parts of task are completed by the group	Undertakes activities largely independently of others	Completes activities and reports to others	Assumes group responsibility as indicated by use of first person plural

Table 2.9 Social Skills in Collaborative Problem Solving (Hesse et al., 2015)

Cognitive skill is also important to the effectiveness and efficiency of collaborative problem solving. Cognitive skills refer to the ways in which problem solvers manage the task and the reasoning skills put to use. Cognitive skills contain task regulation, learning and knowledge building. Hesse et al. (2015) categorize to three levels of collaboration: low, middle, high.



Element	Indicator	Low 0	Middle 1	High 2
Task regulation				
Organises (problem analysis)	Analyses and describes a problem in familiar language	Problem is stated as presented	Problem is divided into subtasks	Identifies necessary sequence of subtasks
Sets goals	Sets a clear goal for a task	Sets general goal such as task completion	Sets goals for subtasks	Sets goals that recognise relationships between subtasks
Resource management	Manages resources or people to complete a task	Uses/Identifies resources (or directs people) without consultation	Allocates people or resources to a task	Suggests that people or resources be used
Flexibility and ambiguity	Accepts ambiguous situations	Inaction in ambiguous situations	Notes ambiguity and suggests options	Explores options
Collects elements of information	Explores and understands elements of the task	Identifies the need for information related to immediate activity	Identifies the nature of the information needed for immediate activity	Identifies need for information related to current, alternative, and future activity
Systematicity	Implements possible solutions to a problem and monitors progress	Trial and error actions	Purposeful sequence of actions	Systematically exhausts possible solutions
Learning and knowledge building				
Relationships (Represents and formulates)	Identifies connections and patterns between and among elements of knowledge	Focused on isolated pieces of information	Links elements of information	Formulates patterns among multiple pieces of information
Rules: "If … then"	Uses understanding of cause and effect to develop a plan	Activity is undertaken with little or no understanding of consequence of action	Identifies short sequences of cause and effect	Uses understanding of cause and effect to plan or execute a sequence of actions Plans a strategy based on a generalised understanding of cause and effect
Hypothesis "what if…" (Reflects and monitors)	Adapts reasoning or course of action as information or circumstances change	Maintains a single line of approach	Tries additional options in light of new information or lack of progress	Reconstructs and reorganises understanding of the problem in search of new solutions

Table 2.10 Cognitive Skills in Collaborative Problem Solving (Hesse et al., 2015)

In the book, Science and Technology Education and Communication_ Seeking Synergy (van derSanden & Vries, 2016), the authors supports that design methods can be used in science and technology communication: “To conclude, design for science and technology education and communication for being a system problem, fits in the traditions and ideas of design in general and of social design and service design particularly, through the resemblance in social processes and according challenges. Science and technology communication, however, lacks a profound basis for system thinking and design thinking” (p. 135).

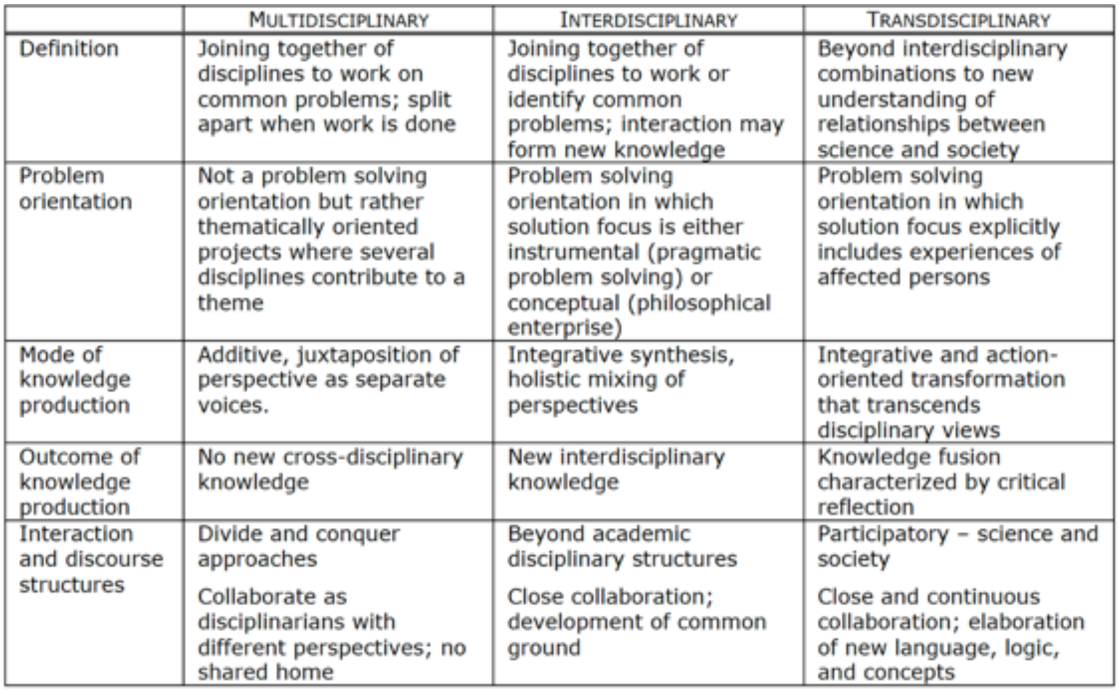
2.5 Crossdisciplinarity, Interdisciplinary and Transdisciplinary

2.5.1 Crossdisciplinarity, Interdisciplinary and Transdisciplinary

Cross-disciplinary approaches aim at the nature of problem, integrating several disciplinaries to synthesize a collective whole. This approach can stimulate innovation and amplify creative potential (Petre, 2004).

The characters of a cross-disciplinary boundary work are: 1) presenting multiple disciplines; 2) the nature of the problem related to several perspectives; 3) making efforts to broaden and limit “boundaries” around problem and the process; 4) inclusion of team members from diverse disciplinary backgrounds (Adams, Mann, Jordan, & Daly, 2009).

Cross-disciplinary practices include multidisciplinarity, interdisciplinarity and transdisciplinarity. A synthesis of cross-disciplinary practices can be regarded as an orientation to the problem, mode and outcome of knowledge production, social interaction structure and discourse practices (Aligica, 2004; Balsiger, 2004; Klein, 2004).



	MULTIDISCIPLINARY	INTERDISCIPLINARY	TRANSDISCIPLINARY
Definition	Joining together of disciplines to work on common problems; split apart when work is done	Joining together of disciplines to work or identify common problems; interaction may form new knowledge	Beyond interdisciplinary combinations to new understanding of relationships between science and society
Problem orientation	Not a problem solving orientation but rather thematically oriented projects where several disciplines contribute to a theme	Problem solving orientation in which solution focus is either instrumental (pragmatic problem solving) or conceptual (philosophical enterprise)	Problem solving orientation in which solution focus explicitly includes experiences of affected persons
Mode of knowledge production	Additive, juxtaposition of perspective as separate voices.	Integrative synthesis, holistic mixing of perspectives	Integrative and action-oriented transformation that transcends disciplinary views
Outcome of knowledge production	No new cross-disciplinary knowledge	New interdisciplinary knowledge	Knowledge fusion characterized by critical reflection
Interaction and discourse structures	Divide and conquer approaches Collaborate as disciplinarians with different perspectives; no shared home	Beyond academic disciplinary structures Close collaboration; development of common ground	Participatory – science and society Close and continuous collaboration; elaboration of new language, logic, and concepts

Table 2.11 Synthesis of Cross-disciplinary Practices (Aligica, 2004; Balsiger, 2004; Klein, 2004)

In the article "Foundations of transdisciplinarity," Manfred A. Max-Neef (2005) explained that "Interdisciplinarity is organized at two hierarchical levels. It thus connotes coordination of a lower level from a higher one" (p. 6).

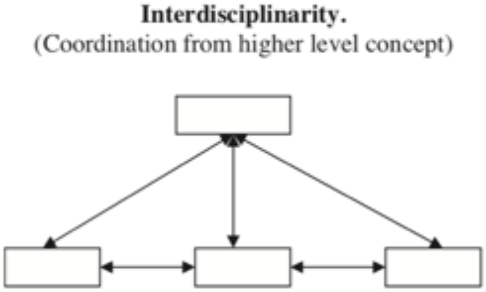
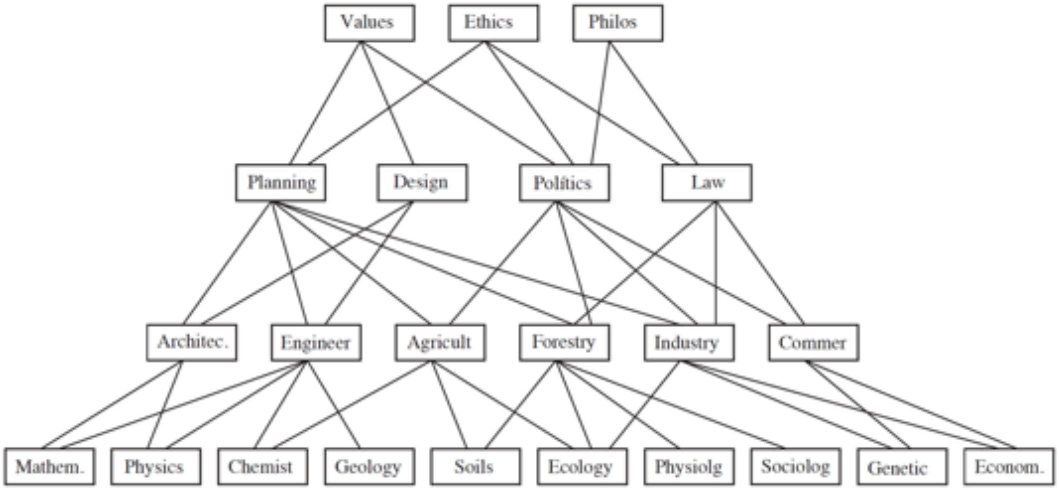


Figure 2.18 Interdisciplinarity Structure (Max-Neef, 2005)

Transdisciplinarity, however, is the result of a coordination between all hierarchical levels (Max-Neef, 2005).



Graph 3. Transdiscipline. Reading the graph from bottom to top, the lower level refers to *what exists*. The second level to *what we are capable of doing*. The third to *what we want to do*. And finally, the top level refers to *what we must do*, or rather, *how to do what we want to do*. In other words, we travel from an *empirical* level, towards a *purposive or pragmatic* level, continuing to a *normative* level, and finishing at a *value* level. Any multiple vertical relations including all four levels, defines a transdisciplinary action.

Figure 2.19 Transdisciplinary Structure (Max-Neef, 2005)

Daniel Stokols (2006) used the graphic below (Figure 2.20) to state the organizational, geographic, and analytic scope of transdisciplinary action research. We can use this graph to figure out where is the position of collaboration.

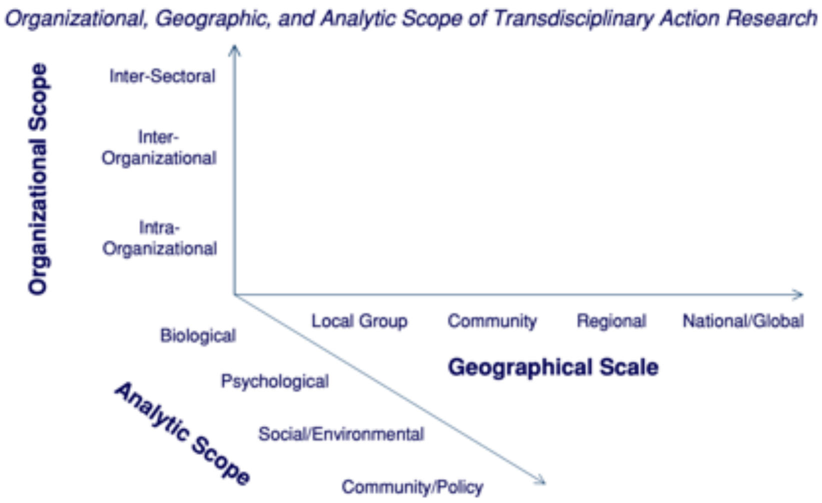


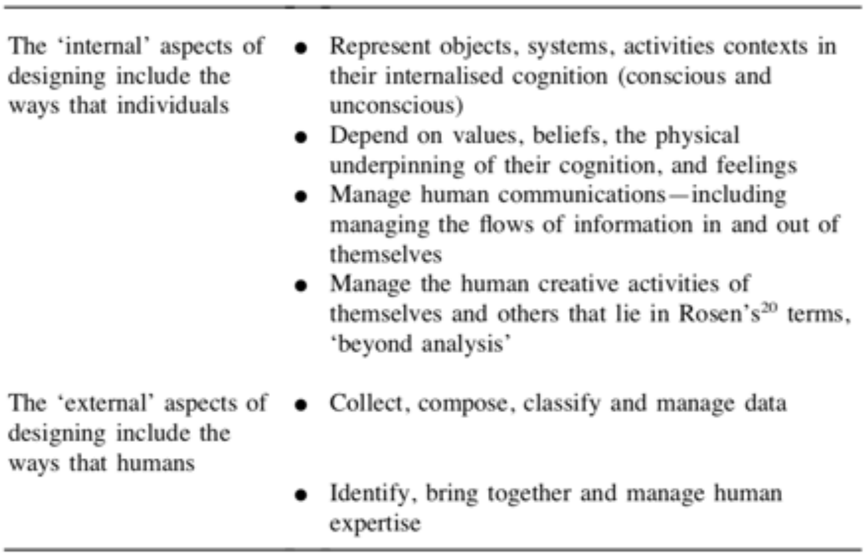
Figure 2.20 Organizational, Geographic Analytic Scope of Transdisciplinary Action Research (Stokols, 2006)

The nine areas underneath provide a framework for identifying the relationships between theories about designing and designs and theories of other disciplines (Love, 2002).

Area of theory about designing and designs	*Disciplines that address this area of theory*
Behaviour of individual *humans*	Biology, Psychology, Anthropology, research into designing, History…
Behaviour of *contexts*	Environmental Studies, Geography, History, Physics, Social Psychology, Sociology, Management, Business Studies, Systems…
Behaviour of *objects*	Engineering, Natural Sciences, History…
Human to *human* interactions	Psychology, research into designing, Sociology, Anthropology, Social Psychology, History, Management, Soft Systems…
Object to *object* interactions	Engineering, Natural Sciences…
Human and *object* interactions	Æsthetics, Ergonomics, Philosophy, Psychology, research into designing, research into designs, Social Psychology…
Human and *context* interactions	Æsthetics, Ergonomics, Psychology, History, Geography, Philosophy, Social Sciences, Anthropology…
Object and *context* interactions	Engineering, Natural Sciences…
Interactions involving *human(s)*, *object(s)* and *contexts* together	Æsthetics, Biology, Engineering, Environmental Studies, Ergonomics, Philosophy, Psychology, Natural Sciences, research into designing, research into designs…

Table 2.12 Areas of theories and discipline (Love, 2002)

The categories of Table 2.11 can be further refined by differentiating between ‘internal human processes’ and the ‘external aspects of behavior of individuals and groups’ (Table 2.13).



The 'internal' aspects of designing include the ways that individuals	• Represent objects, systems, activities contexts in their internalised cognition (conscious and unconscious) • Depend on values, beliefs, the physical underpinning of their cognition, and feelings • Manage human communications—including managing the flows of information in and out of themselves • Manage the human creative activities of themselves and others that lie in Rosen's^{20} terms, 'beyond analysis'
The 'external' aspects of designing include the ways that humans	• Collect, compose, classify and manage data • Identify, bring together and manage human expertise

Table 2.13 Internal and External Aspects of Human Designing (Love, 2002)

Scholz et al. (2001) proposed to initial Transdisciplinarity Colleges stimulate practitioners and scientists to develop, practice and experiencing transdisciplinarity. Within limited periods of time (several weeks or years), such labs in transdisciplinarity college can deal with problems transdisciplinary (Figure 2.21). We can use this as a potential structure to illustrate the collaboration between design and science.

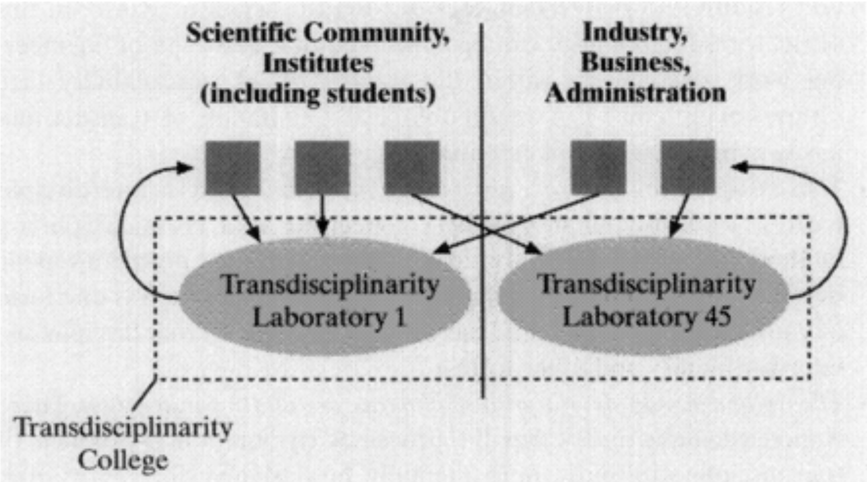
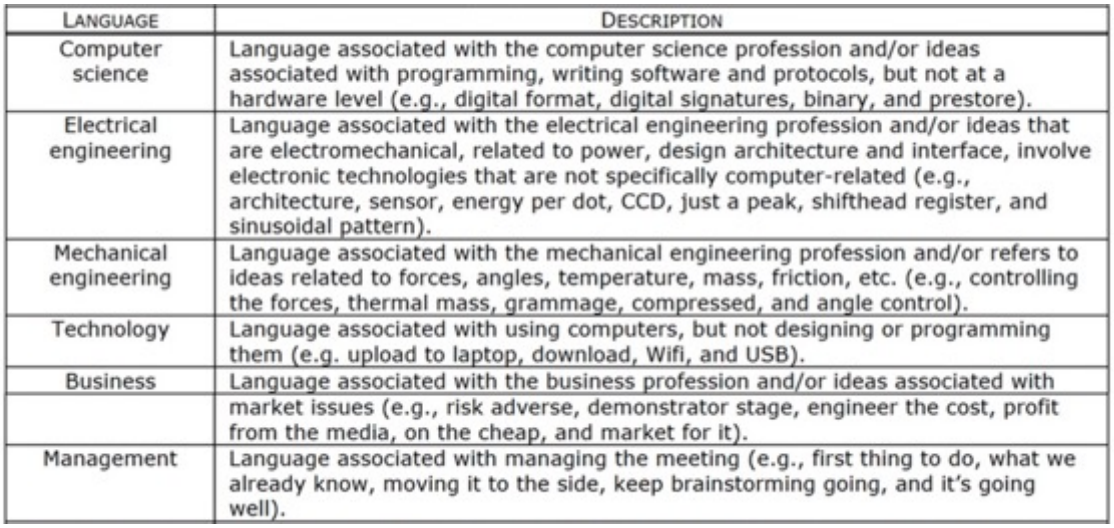


Figure 2.21 Design for a Transdisciplinarity College with Temporary Transdisciplinarity Laboratories Based on a Symmetric Participation of Science and Society (Scholz et al., 2001)

2.5.2 Characteristics Represent Cross-disciplinary

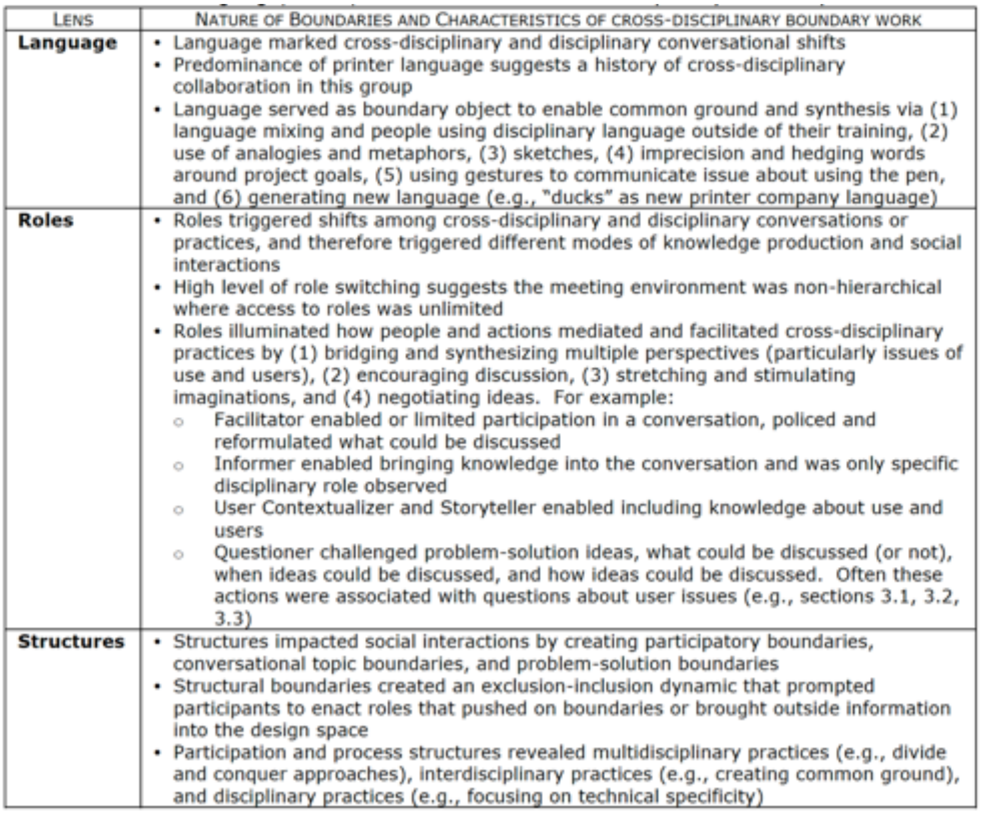
Three robust characterizations, language, roles and structures, can illuminate aspects of cross-disciplinary boundary work. Language classifications represent what participants talk about from a disciplinary perspective, and how it was communicated (Aligica, 2004; Balsiger, 2004; Klein, 2004). Additionally, understanding the unconventional form of language (slang/jargon), especially in its cross-cultural mutation, is important to communication in design processes in today's global context (Dastmalchi, 2017). For example, some organizations which are great at tackling internal problem can take care of problems that cross silo challenges and touch points (Lockwood & Papke, 2017).



LANGUAGE	DESCRIPTION
Computer science	Language associated with the computer science profession and/or ideas associated with programming, writing software and protocols, but not at a hardware level (e.g., digital format, digital signatures, binary, and prestore).
Electrical engineering	Language associated with the electrical engineering profession and/or ideas that are electromechanical, related to power, design architecture and interface, involve electronic technologies that are not specifically computer-related (e.g., architecture, sensor, energy per dot, CCD, just a peak, shifthead register, and sinusoidal pattern).
Mechanical engineering	Language associated with the mechanical engineering profession and/or refers to ideas related to forces, angles, temperature, mass, friction, etc. (e.g., controlling the forces, thermal mass, grammage, compressed, and angle control).
Technology	Language associated with using computers, but not designing or programming them (e.g. upload to laptop, download, Wifi, and USB).
Business	Language associated with the business profession and/or ideas associated with
	market issues (e.g., risk adverse, demonstrator stage, engineer the cost, profit from the media, on the cheap, and market for it).
Management	Language associated with managing the meeting (e.g., first thing to do, what we already know, moving it to the side, keep brainstorming going, and it's going well).

Table 2.14 Language Classification Scheme (Aligica, 2004; Balsiger, 2004; Klein, 2004)

Role classifications describe participants' actions throughout cross-disciplinary practices. Adams et al. (2009) classify the roles to facilitator, informer, evaluator, idea generator, interpreter, questioner, Storyteller and user contextualizer. In this thesis, because designer and researcher each play some of those roles, I separate the roles into designers, users and experts. Structure classifications refer to the structure of the design space and organizational structure of meeting. The language, role, and structure in cross-disciplinary boundary work impact and reveal outcome differently (Adams et al., 2009).



LENS	NATURE OF BOUNDARIES AND CHARACTERISTICS OF CROSS-DISCIPLINARY BOUNDARY WORK
Language	• Language marked cross-disciplinary and disciplinary conversational shifts • Predominance of printer language suggests a history of cross-disciplinary collaboration in this group • Language served as boundary object to enable common ground and synthesis via (1) language mixing and people using disciplinary language outside of their training, (2) use of analogies and metaphors, (3) sketches, (4) imprecision and hedging words around project goals, (5) using gestures to communicate issue about using the pen, and (6) generating new language (e.g., "ducks" as new printer company language)
Roles	• Roles triggered shifts among cross-disciplinary and disciplinary conversations or practices, and therefore triggered different modes of knowledge production and social interactions • High level of role switching suggests the meeting environment was non-hierarchical where access to roles was unlimited • Roles illuminated how people and actions mediated and facilitated cross-disciplinary practices by (1) bridging and synthesizing multiple perspectives (particularly issues of use and users), (2) encouraging discussion, (3) stretching and stimulating imaginations, and (4) negotiating ideas. For example: ○ Facilitator enabled or limited participation in a conversation, policed and reformulated what could be discussed ○ Informer enabled bringing knowledge into the conversation and was only specific disciplinary role observed ○ User Contextualizer and Storyteller enabled including knowledge about use and users ○ Questioner challenged problem-solution ideas, what could be discussed (or not), when ideas could be discussed, and how ideas could be discussed. Often these actions were associated with questions about user issues (e.g., sections 3.1, 3.2, 3.3)
Structures	• Structures impacted social interactions by creating participatory boundaries, conversational topic boundaries, and problem-solution boundaries • Structural boundaries created an exclusion-inclusion dynamic that prompted participants to enact roles that pushed on boundaries or brought outside information into the design space • Participation and process structures revealed multidisciplinary practices (e.g., divide and conquer approaches), interdisciplinary practices (e.g., creating common ground), and disciplinary practices (e.g., focusing on technical specificity)

Table 2.15 Language, Roles, and Structure in Cross-disciplinary Boundary Work (Adams et al., 2009)

Chapter 3: Guideline Development

This chapter will start by analyzing the logic of design to why problem identification is important in collaboration between designers and researchers. Then, a number of steps in the problem refinement process are developed to help designers to collaborate with researchers. Even though those steps are based on the previous research, this is a new approach to designers and scientific researchers. With the boundary of different logic reasoning and thinking process, designers and researchers use different ways to solve problems. Armed with different knowledge, they both are siloed. This guideline aims at helping designers and researchers to cross boundaries and silo challenges and solve the right problem *(Lockwood & Papke, 2017).* The problem refinement process is applied after getting the collaborative outcome without it. This guideline also allows designers to use specific steps to continuously refine problems throughout the problem-solving process. Finally, the pattern of designers and scientific researchers' collaboration is discussed.

3.1 The Logic of Design

Design is an activity different from scientific discovery. The major difference comes from the logic (Beckett, 2017). Analyzing the logic of design helps us find out the gap of reasoning methods between designers and scientific researchers and then figure out an approach to fill the gap. Based on Chapter 2.1.1, scientists and researchers use inductive reasoning to discover the laws of nature. They also use deductive reasoning to demonstrate the laws they find. Designers, however, not only use deductive reasoning and inductive reasoning, but also use abductive reasoning according to Dorst (2011).

In order to analyze designers' and researchers' reasoning methods in the same equation, I use the Golden Circle to illustrate. From outside-in, we identify 'Result' based on the things (an object, a service, a system) and the 'Principle'. This matches the process from 'What' and 'How' to find 'Why'. Since 'How' in the Golden Circle can be considered as the inside part, we can still conclude the inductive reasoning process outside-in (Figure 3.1).

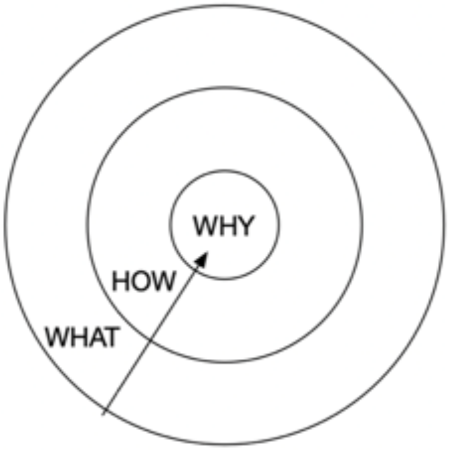
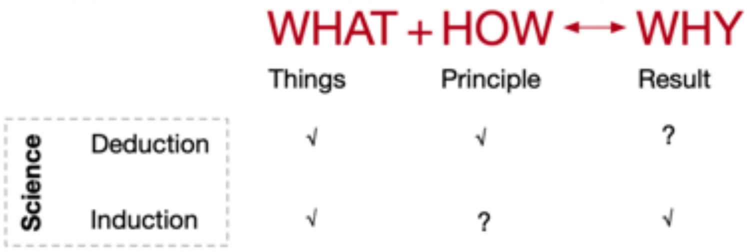


Figure 3.1 The Golden Circle Describe Outside-in Reasoning Process

In this thesis, we use a new equation: 'What' to do plus 'How' to do it leads to 'Why' to do that. According to Dorst (2011), deduction and induction can be described as Figure 3.2 presents.



WHAT + HOW ←→ WHY

		Things	Principle	Result
Science	Deduction	√	√	?
	Induction	√	?	√

Figure 3.2 Deduction and Induction in the New Equation

Alexander (1964) used to say: "Scientists try to identify the components of existing structures. Designers try to shape the components of new structures" (p. 130). Other than the reasoning methods mentioned above, designers also use comparatively complex reasoning method: abductive reasoning. Based on the Golden Circle, this is a process of inside-out: from ‘Why’ we do it to ‘What’ the things are (Figure 3.3).

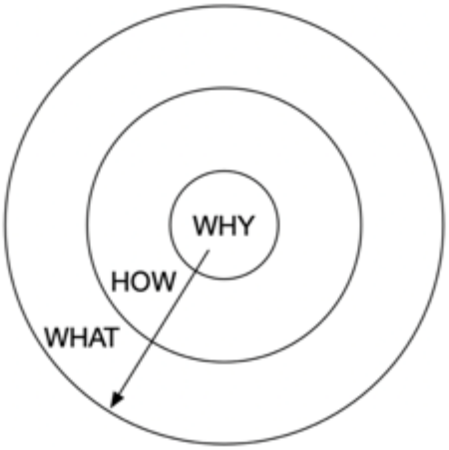
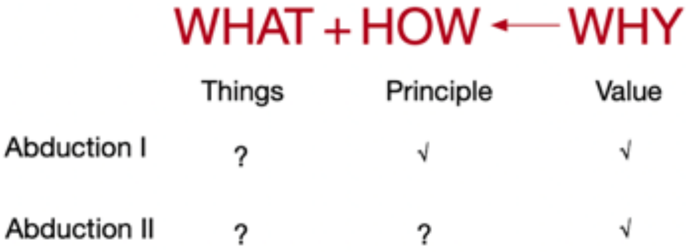


Figure 3.3 The Golden Circle Describe Inside-out Reasoning Process

Based on the observation of value, this thinking process helps designers to predict the explanation and sometimes to find the working principle. Dorst (2011) called these two abductive reasoning processes as Abduction I and Abduction II.

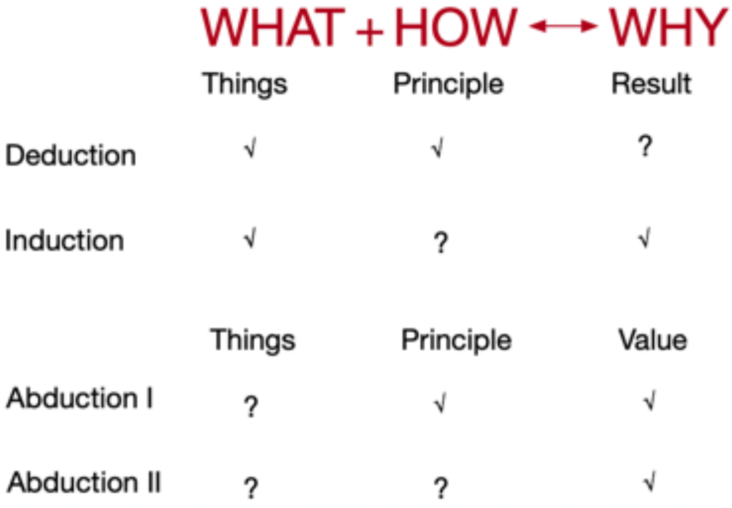


WHAT + HOW ← WHY

	Things	Principle	Value
Abduction I	?	√	√
Abduction II	?	?	√

Figure 3.4 Abduction I and II in the New Equation

When designers try doing some productive thinking and be creative, ‘Why’ designers want to do what they do represents the ‘Value’ they want to achieve. But when designers use what they observed to induce and demonstrate the outcome or law like scientists and researchers, the ‘Why’ resembles ‘Result’. So, ‘Why’ we do that includes the ‘Value’ we want to create and the ‘Result’ can be observed.



WHAT + HOW ←→ WHY

	Things	Principle	Result
Deduction	√	√	?
Induction	√	?	√
	Things	Principle	Value
Abduction I	?	√	√
Abduction II	?	?	√

Figure 3.5 Deduction, Induction and Abduction in the New Equation

When scientific researchers are helped by designers, the first goal is putting them in the same picture of design reasoning methods and finding the same value they want to achieve. However, the 'Value' we want to achieve is not properly identified or changed throughout the design process. The design process is a dynamic process. This process named as Recursion reflects the designer's presumption from the inference of the case and partial rule from a result (Zeng & Cheng, 1991). Dorst (2011) mentioned the answer how to create the value we are striving for is having the specific perception of a problem situation and adopting the working principle with that situation. Problem situation can change and even be dynamic.

Beckett mentioned the design process is dialectical. It contains two contradictory things: problem and the goal (Beckett, 2017). We can recognize this dialectical process as a recursive process between finding the problem we face and defining value we want to achieve. In this thesis, this process is from the value scientific researchers want to achieve to the refined value designers and scientific researchers both recognize to achieve. In this process, finding *the right problem*, which is broadening or confining the problem context, is the most important to do. After 'Value' is refined, abductive reasoning can be applied. In this circumstance, the logic of design becomes a recursive reasoning process.

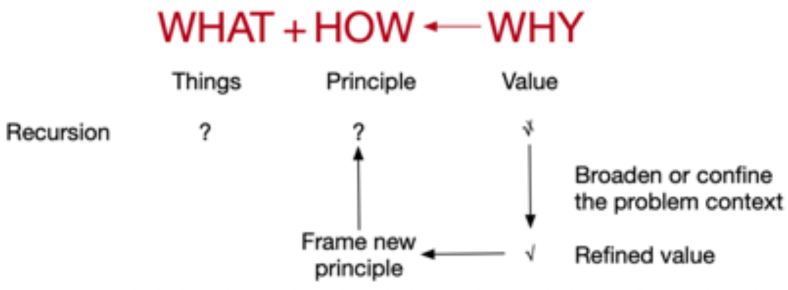


Figure 3.6 Recursion in the New Equation

To sum up, the logic of design is shown in Figure 3.7. Even though designers sometimes use deductive reasoning to demonstrate the design they created and inductive reasoning to generate the design principles based on design cases, the unique reasoning skills they use are abduction and recursion. So, when collaborating with scientific researchers, designers' response is helping researchers realize they can solve problems by applying deduction and induction which researchers are used to, as well as abduction and recursion.

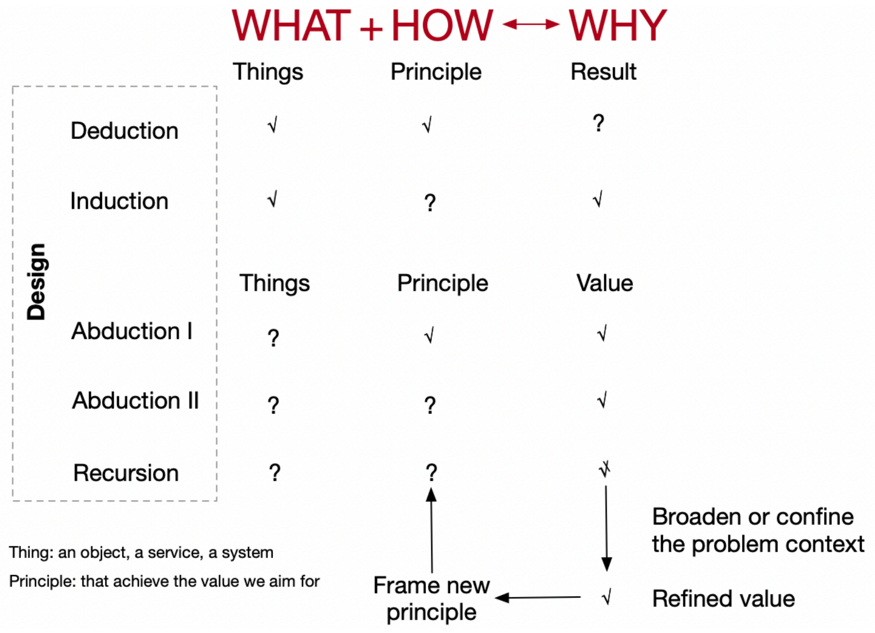


Figure 3.7 The Logic of Design in the New Equation

3.2 Problem Identification

When we decide to refine the ‘Value’ we want to create, a process is needed to identify the problem we want to solve. There is a gap between what is the problem and what the problem ought to be. The process to fill this gap is the problem identification. In order to fill the gap, two things have to be realized: defining the problem and locating the problem (Rittel & Webber, 1973).

In this thesis, the only difference between Recursion and Abduction is the gap from ‘What the ‘Value’ is’ to ‘What the ‘Value’ ought-to-be’. By defining the problem and locating the problem, the gap can be filled. Since the initial problem is usually offered by scientific researchers who look for designers’ assistance with, this process can be named as the problem refinement process. There are two goals of this process: the first one is helping scientific researchers find the ‘Value’ they have not thought of; the second one is helping designers recognize the problem definition, location and context. Putting designers and researchers in the same picture can make the problem-solving process or design process run smoothly.

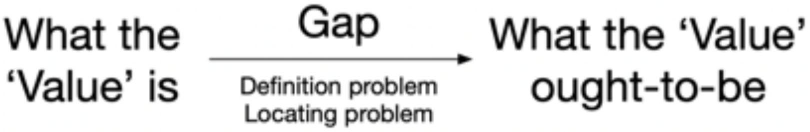


Figure 3.8 The Difference between Recursion and Abduction

3.3 Problem Refinement Process

In order to fill the gap between ‘What the ‘Value’ is’ and ‘What the ‘Value’ ought-to-be’, the problem refinement process is developed. This process includes three main steps: initial problem definition, goal and context further exploration, refined problem. The refined problem iterates throughout the process (Figure 2.9). The initial problem definition includes a selection of representation modalities and jargon explanation. The goal and context further exploration includes defining the goal and problem context articulation. The problem context articulation starts from problem decomposition, finding constraints to searching knowledge inventory. After richening the initial problem definition context and decomposing the goal and the problem to develop a detailed context, a refined problem comes out and is prepared for problem-solving process. The new context and problem location of the refined problem needs to be checked before and after the problem-solving process. It is a process to keep the refining problem step iterating.

3.3.1 Initial Definition of the Problem

At the beginning of collaboration, scientific researchers come with the initial problem statement when they tend to find help from designers. However, the statement of the initial problem usually cannot express the whole idea sufficiently. To solve this issue, the first thing to do is decide which types of stimulus representation modalities based on Table 2.3. There are five types of modalities: Verbal, Textual & Visual, Visual, Multimodal and Physical (Dankfort et al., 2018). Nevertheless, and the closer researchers worked together, the more likely they collaborate (Binz-Scharf et al., 2015) and the more choices of modalities they can use. By using one of them or some of them, designers can figure out the initial problem context. Considering the geographical scale based on Figure 2.20, for example, a local group can use visual modality to refine the problem face to face. However, if they cannot meet together, they probably can use email or other communication to exchange description of problem context.

After use of different modalities explains the initial problem, the next barrier between designers and scientific researchers is understanding jargon (professional language) from each other. Designers can use Table 2.9 to figure out what type of language the scientific researchers need to explain, and vice versa, designers should also offer the explanation of design jargons like storyboard, sketches, prototype and design thinking.

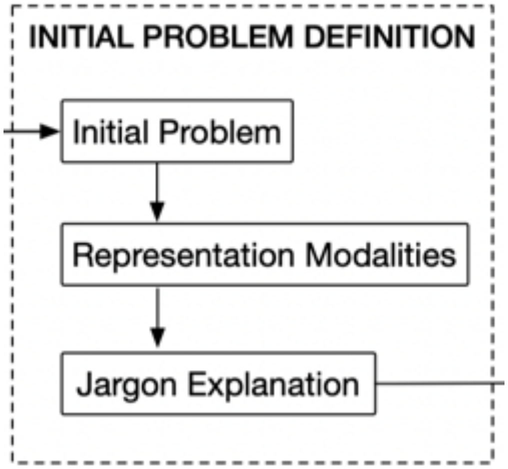


Figure 3.9 Initial Problem Definition

To sum up, the initial definition of the problem includes the initial problem statement, selection of representation modalities, and jargon explanation.

3.3.2 Goal and Context Further Exploration

After the initial definition of the problem, designers have a general picture of the initial problem and its initial context. The next step is the goal and context further exploration. The first procedure is generating the goal acknowledged by both designers and scientific researchers. This goal is a general statement based on designers and researchers both understanding the initial problem and its context.

In cross-disciplinary practice, the design team should make efforts to broaden and limit "boundaries" around problem (Adams et al., 2009). In that case, the second procedure is problem context articulation, which contains three steps. This procedure helps digging up the opportunities and constraints of the problem. The first step of this procedure is finding sub-goals. Based on Jonassen's (1997) problem-solving process from Figure 2.11, problem decomposition is the first step when they try to reduce the discrepancy between the current goal statement and the refined statement of the problem. The problem-as-presented first needs to be 'deconstructed' (Hekkert & van Dijk, 2011) and then it can become amenable to solution. In this process, designers can be the leader to help researchers think divergently instead of just applying deductive reasoning and inductive reasoning and focusing on limited solutions. I use a part of the Double Diamond (Figure 2.2) graphic to illustrate how designers help researchers extend the problem space (Figure 3.10).

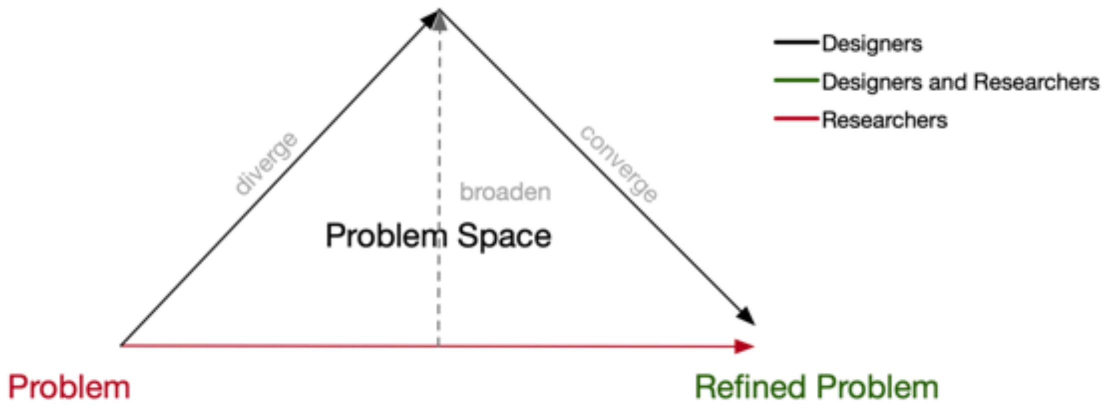


Figure 3.10 Extend Problem Space

There are still some things to consider after divergent thinking: even though designers help scientific researchers to extend the problem space by decomposing the problem, they still do not define the constraints of these sub-goals. Without constraints the refined problem may lead to unnecessary problem space which leads to solutions that are not applicable. So, scientific researchers can assist designers to figure out the limitation in the problem space and capabilities and facilities of these sub-goals. For example, time consumption, human labor, the money issue or limitation of knowledge are all the constraints which keep researchers from achieving the goal that need to be considered. So, the second step of this procedure is analyzing the constraints based on sub-goals generated by the first step of this procedure. This procedure is helping

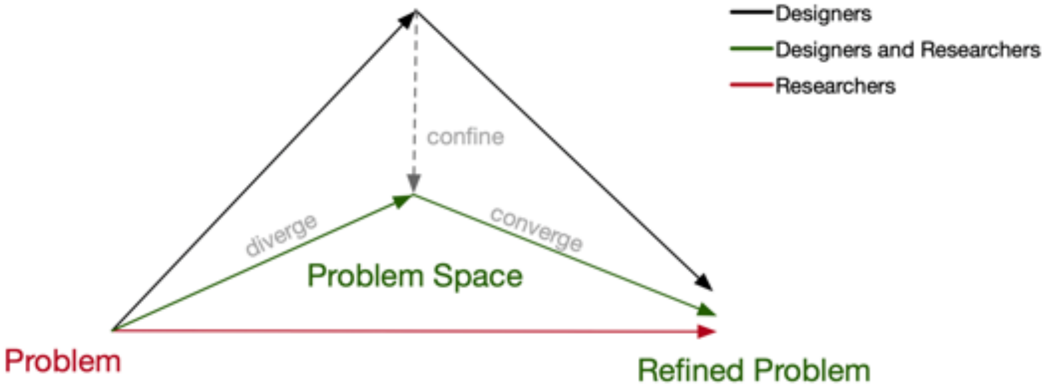


Figure 3.11 Shrink Problem Space

By articulating sub-goals and constraints, the designer and researchers can locate the proper problem space. The third step of this procedure is search and find related knowledge inventory. This can be domain knowledge, structural knowledge, procedural knowledge and systemic knowledge (Table 2.4). This information can be offered by researchers, designers and experts who are involved in the problem-solving process. Taking them into consideration will help designers and researchers to have enough information for the problem-solving process.

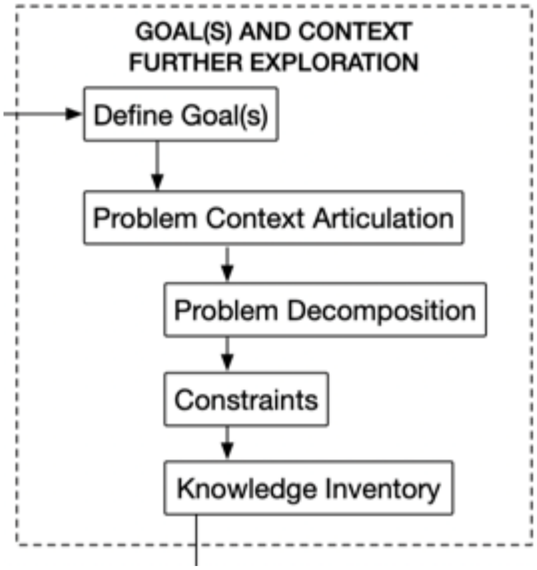


Figure 3.12 Goal(s) and Context Further Exploration

To sum up, goal and context include two procedures which are define main goal(s) and problem context articulation. The second procedure has three steps: problem decomposition, defining constrains and knowledge inventory adding.

3.3.3 Refined Problem and Recursion

By applying initial problem identification, designers and scientific researchers stand in the same picture to refine the problem. Then by exploring goals and further context, designers and researchers can use their own knowledge to broaden and then confine the problem space. In this way, the refined problem will come out in the end of the first circle of the problem refinement process. However, problem location which means the networks of the trouble really lies (Rittel & Webber, 1973) or the context pf problem may change throughout the process. Along with the changing, the redefined problem is also changed. Along with the problem iterations, the 'Value' changes. This is the reason why recursion adds to the logic of design in Chapter 3.1.

In order to promote the iteration, two checkpoints are added to this approach. The first checkpoint happens after we have refined problem. By checking whether new context is added and the problem location changes, designers and researchers need to decide if they need to reevaluate the refined problem and re-access part of the process from initial problem definition or goal and further context exploration. The other checkpoint occurs after solution comes out. Researchers and designers can use this checkpoint to decide whether they should finish this project or keep developing by refining the problem again.

At some time after the project finishes, new context may show up or problem location changes. Designers and researchers can choose to start to refine the project again and begin to refine the problem that is already refined last time.

As Figure 3.13 shows, this is approach to fill the gap between 'What the 'Value' is' and 'What the 'Value' ought-to-be'. Starting from the initial problem definition to further goal and context further exploration, a refined problem can be found. By checking whether the new condition occurs, designers and researchers can decide if they can start solving this refined problem or keep refining. After the solution is generated, they can decide to finish this project or re-access the new condition to continue their development. These circle paths show the recursion of the design logic. With certain situations, the new context will affect the change of initial problem definition. In that case, I add two dash lines to direct to the very beginning of the the problem refinement process.

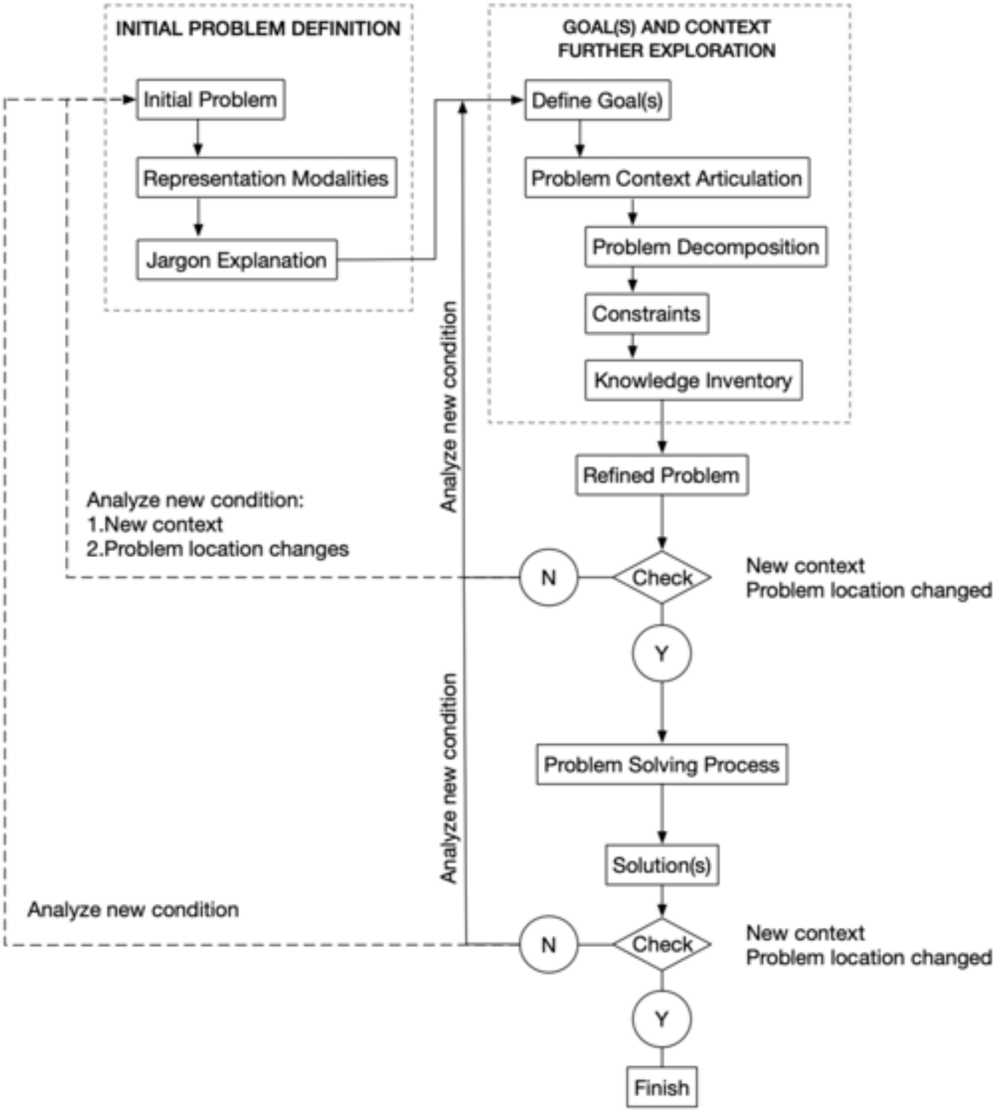


Figure 3.13 The Problem Refining Process

3.4 The Collaboration Developing Process

Without the problem refinement process, by relying on deductive reasoning and inductive reasoning researchers can only have their initial problems with their anticipated solutions. In this circumstance, designers cannot use their design processes to find the better solutions. The collaborative development process between designers and scientific researchers becomes a linear process without divergent and convergent thinking happening in the design process. Researchers are predominant over the collaborative team. The graphic shows like this:

Figure 3.14 Linear Problem-solving Process

By applying the problem refinement process, designers can assist researchers to extend the problem space, which leads to the broadened solution space. At the same time, researchers can also confine the problem space which can save resources (i.e. time, money, labor) that would otherwise be used for inapplicable solutions generation.

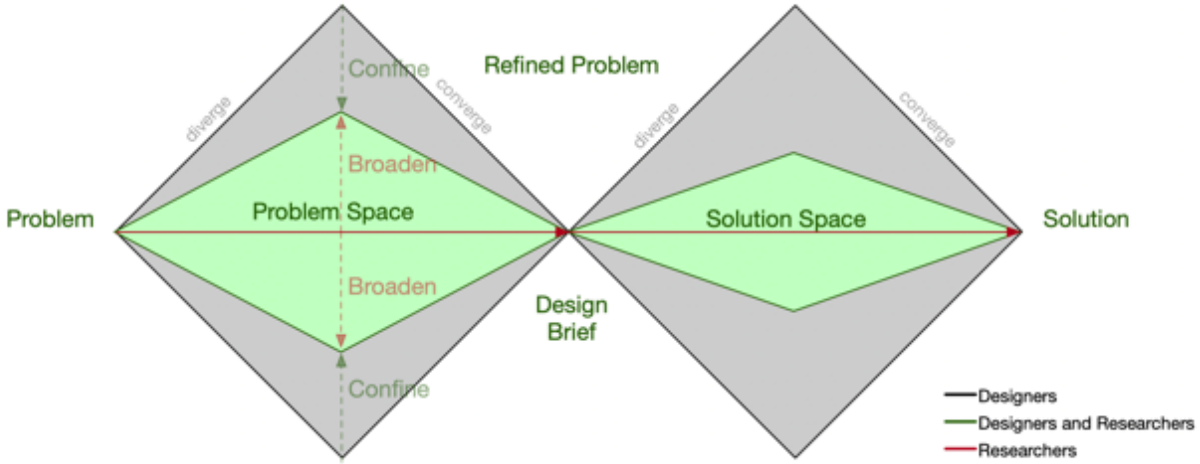


Figure 3.15 Refined Problem-solving Process

In this thesis, we will not talk a lot about the details of the problem-solving process in

Chapter 3 since we can use the process from Chapter 2.2. Additionally, this process also may include one or some of design processes we mentioned in Chapter 2.1.2 as designers are involved in the collaboration. Based on different attributes of projects, designers can choose a different design process to use. For example, for product development, they can consider Table 2.2; for IT development they can consider Figure 2.4; for small projects, they can use the Sprint design process to get the solution quickly. Those are the processes they can use after refining the problem.

3.5 Relationship between Design and Science Collaboration

In this thesis, design and science collaboration can be seen as an interdisciplinary model which shows as one form of cross-disciplinary models from Table 2.11. Based on the model of Figure 2.18, designer can play as a coordinator between scientific researchers. However, researchers can assist each other in collaboration when their expertise is needed. In that case, when designers collaborate with scientific researchers towards the development of experimental tools and practices, the graphic of collaboration between design and science appears as in Figure 3.16:

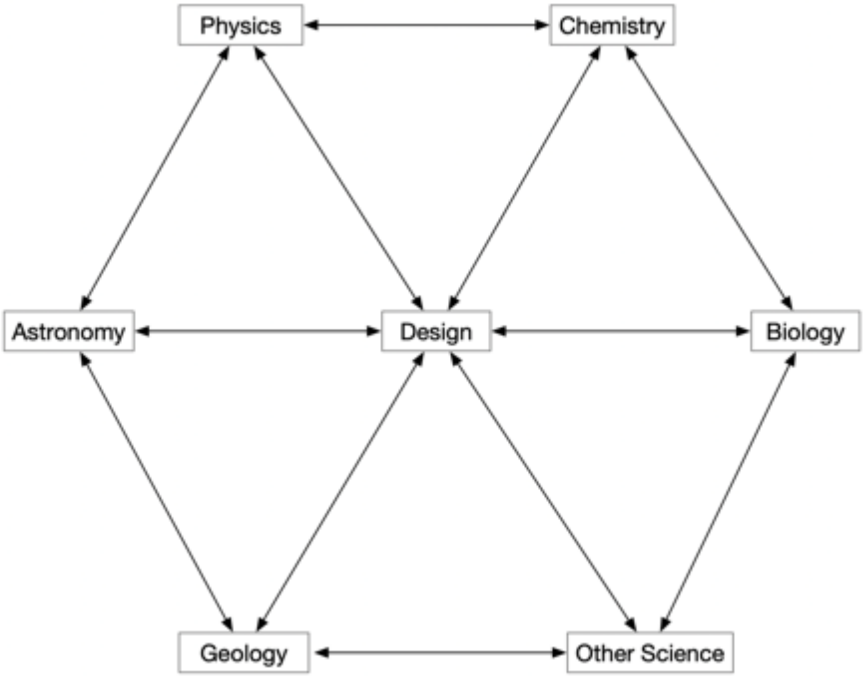


Figure 3.16 Collaboration between Design and Science

The scientific researchers in this system can be the users to initiate the problems. They can also be experts for other researchers' problems to involve design development and offer professional opinions. In that context, experts can solve problems together. Furthermore, designers can offer design processes and design skills to assist them. The roles of designers and researchers are shown in Figure 3.17.

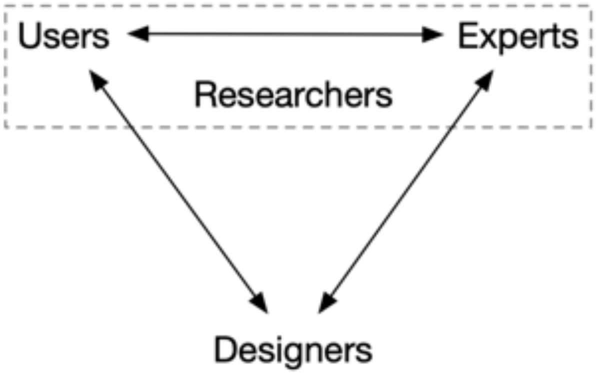


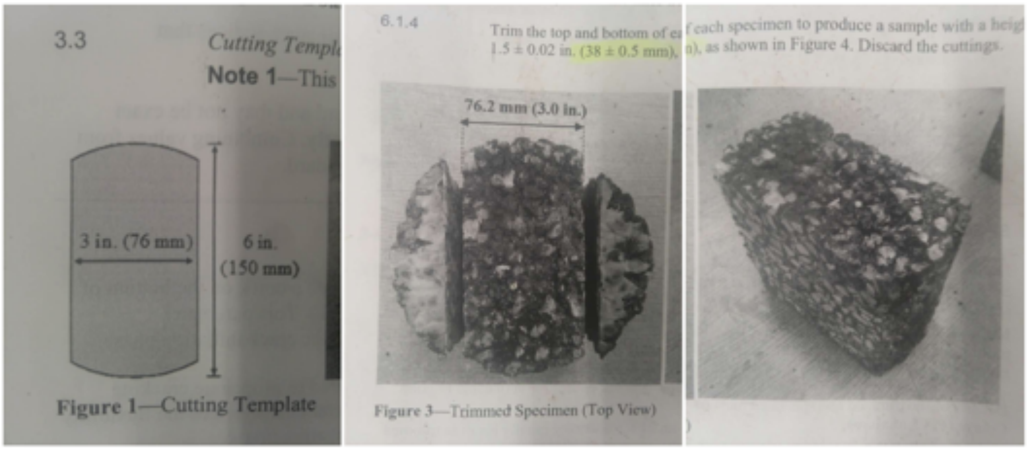
Figure 3.17 Roles of Designers and Researchers

Chapter 4: A Demonstration of Design Guideline

I used to make a This chapter uses a case of a measurement template I made to design to help a researcher from NCAT (National Center for Asphalt Technology) save time in preparing specimens to demonstrate the approach described in the last chapter. By applying the problem refining process mentioned in the Figure 3.13, I am able to help the NCAT researchers to develop their measurement template from a handmade one which is just close to the required size to a machine-made template which is the exact requirement size and has significant improvement in ease of use.

4.1 Initial Definition and Solution

In the spring of 2017, one of my friends who is a researcher in NCAT asked me if there is a 3D printer in my department. He wanted to print a model. After offering the photo of the module, he explained to me he would like to make an exact same template that has a similar shape as Figure 4.1 and 1.5 inch thickness.



Trim the top and bottom of ea each specimen to produce a sample with a heig
1.5 ± 0.02 in. (38 ± 0.5 mm), n), as shown in Figure 4. Discard the cuttings.

Figure 4.1 Template shape

In consideration of the easy handmade shape and the expensive 3D printing material, I used a table saw and sander to make a template made from a piece of polyurethane foam shown in Figure 4.2. But he asked if hard material like metal is available. Since I do not have any pieces of metal available, I used a piece of wood to make another template (Figure 4.3) for him in the workshop of the industrial design department.

Figure 4.2 A Piece of Polyurethane (Left) and Template Made of Polyurethane Foam (Right)

Figure 4.3 Template Made by Wood

According to his feedback, this piece of wood template improves his efficiency. However, as a designer, this is a rather passive way to help scientific researchers. It is a way designers could not fully use their design skills. According to the last chapter, when researchers and designers have different reasoning methods, researchers are not familiar with abduction and recursion. With the ‘thing’ researched and the ‘value’ he wanted to create, researchers only focus on using their solutions to test. This leads researchers to ask for designers’ help with their pre-defined problems and anticipated solutions. The designers cannot do much about it unless they are relying on researchers’ judgement. The researchers’ predominance sometimes makes the designers not fully understand why they are doing that project.

4.2 Initial Problem Definition

The case mentioned above became the stimuli to push me to develop the approach described in last chapter (Figure 3.13). Then I use this approach to find out the context of the NCAT researcher’s initial problem, shown in Figure 4.4.

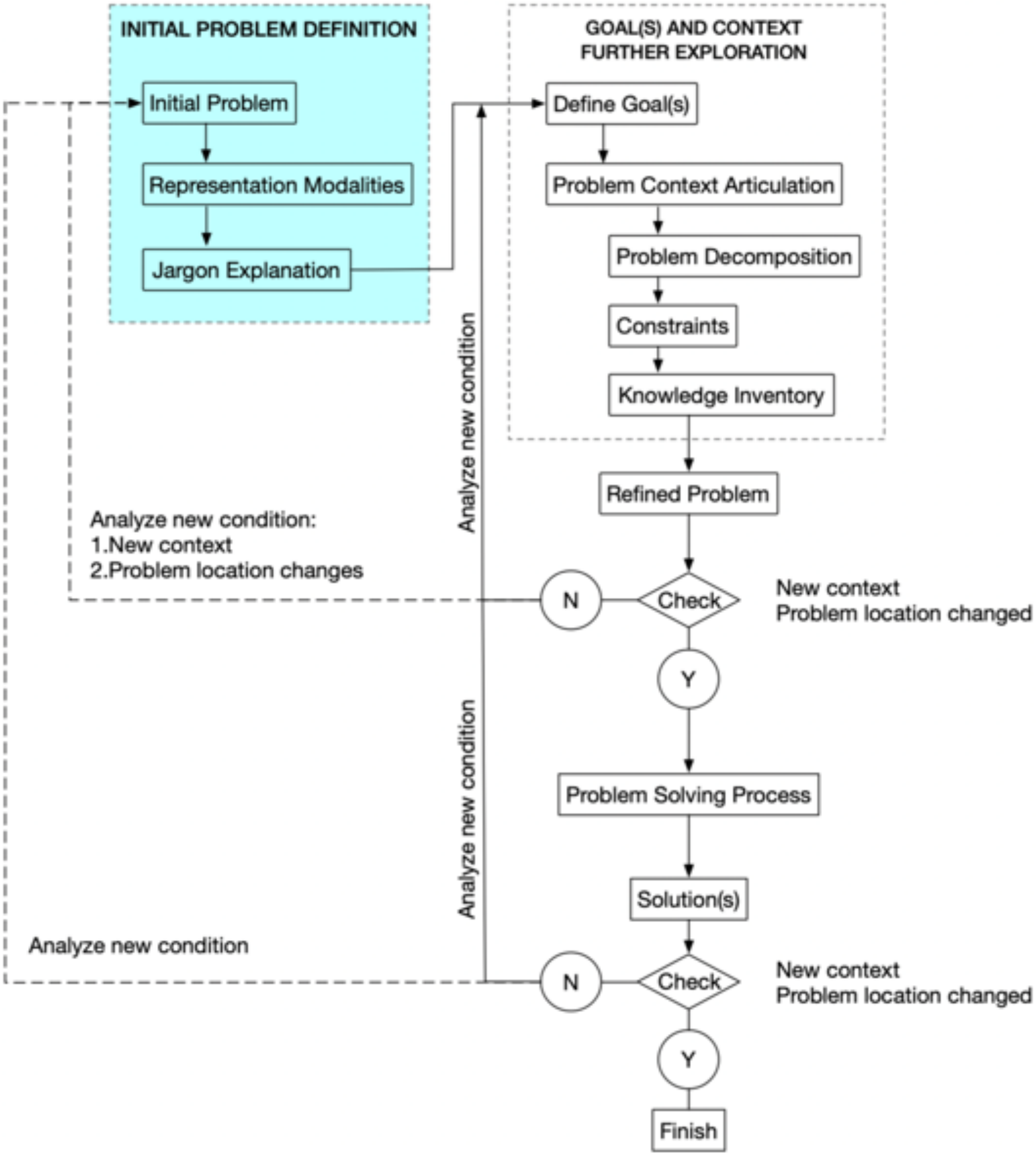


Figure 4.4 Initial Problem Definition in the Problem Refinement Process

4.2.1 Representation Modalities

According to the Chapter 3.3.1, I chose to search online and visit the NCAT facility to find out what the initial problem comes from. The information shown in Chapter 4.2.1 and 4.2.2 comes from the NCAT website, the pictures taken from the NCAT laboratory, and the description and explanation from researchers in the NCAT.

“NCAT's mission is to provide innovative, relevant and implementable research, technology development and education that advances safe, durable and sustainable asphalt pavements” as shown on the NCAT (2019) website.

Figure 4.5 NCAT Pave Test Track (CARGILL)

A researcher in the NCAT facility showed me the procedure of researchers’ daily experiments. Before they tested asphalt samples on the test track, they have to develop different formulas of asphalt samples. They put each formula sample in one steel plate. Each plate is a raw sample of asphalt to test. One of the tests is called the Overlay Test (OT). To prepare for the test, researchers put the sample in a mold and heat the sample in an oven (Figure 4.6). After cooling off, the specimen is shown in Figure 4.7.

Figure 4.6 Specimen Shaping before Overlay Test

Figure 4.7 Cylinder Specimen

Then they used the saw to cut twice, leaving the middle part 3 inches wide and discarding the cuttings (Figure 4.8).

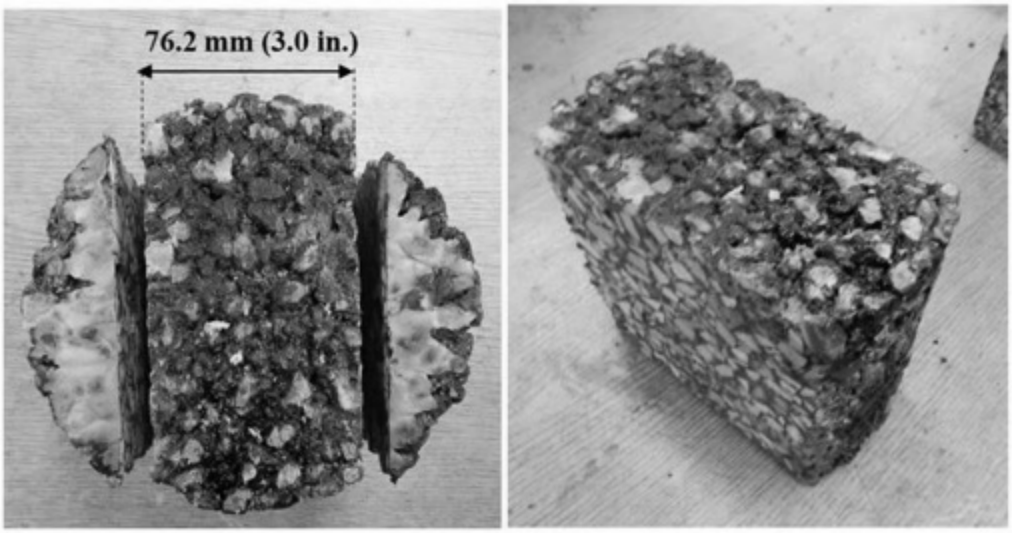


Figure 4.8 Trimmed Specimen 1 (TxDOT, 2017)

After that, they trimmed the specimen top and bottom part and left the middle part at 1.5 inches (Figure 4.9). The middle part is used for testing.

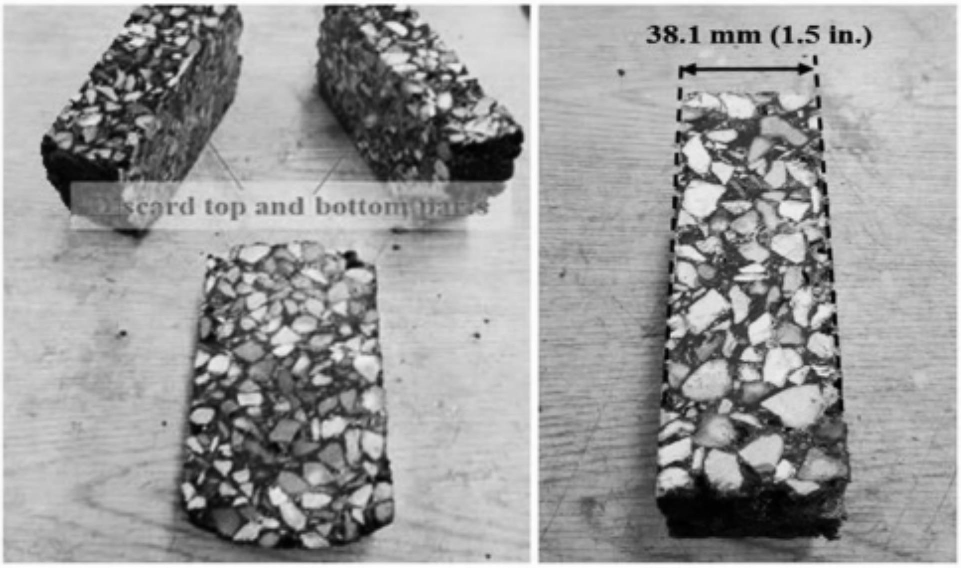


Figure 4.9 Trimmed Specimen 2 (TxDOT, 2017)

4.2.2 Jargon Explanation

The reason to test the specimen is to calculate the critical fracture energy and the crack resistance index. So, jargon explanation is needed.

Critical Fracture Energy (Gc)—the energy required to initiate a crack on the bottom of the specimen at the first loading cycle of the overlay test (OT). This parameter characterizes the fracture properties of the specimen during the crack initiation phase (TxDOT, 2017) .

Crack Resistance Index (CRI)—the reduction in load required to propagate cracking under the cyclic loading conditions of the OT. This parameter characterizes the flexibility and fatigue properties of specimens during the crack propagation phase (TxDOT, 2017).

The processes to get the Gc and CRI are like this: the first is placing a 4mm wide tape along the middle of the specimen; then the specimen is glued on the base plate (Figure 4.10) by epoxy (a kind of glue) avoiding the tape (Figure 4.11); finally removing the tape and placing a 5-lb weight on the top of specimen (Figure 4.12).

Figure 4.10 Base Plate (TxDOT, 2017)

Figure 4.11 Glue and Align the Specimen (TxDOT, 2017)

Figure 4.12 Weighted Specimen (TxDOT, 2017)

Then the researcher removes the tape and uses a razor to cut excess epoxy, and the specimen is ready for Overlay Test (OT).

4.3 Goal and Context Further Exploration

At the stage of goal(s) and further context exploration, we move the understanding of the problem forward. As a designer, I let them realize what goal they can achieve and what issues researchers could address. The researchers help me to organize the constraints and richen the knowledge inventory. These become a great preparation for the problem-solving process in the future.

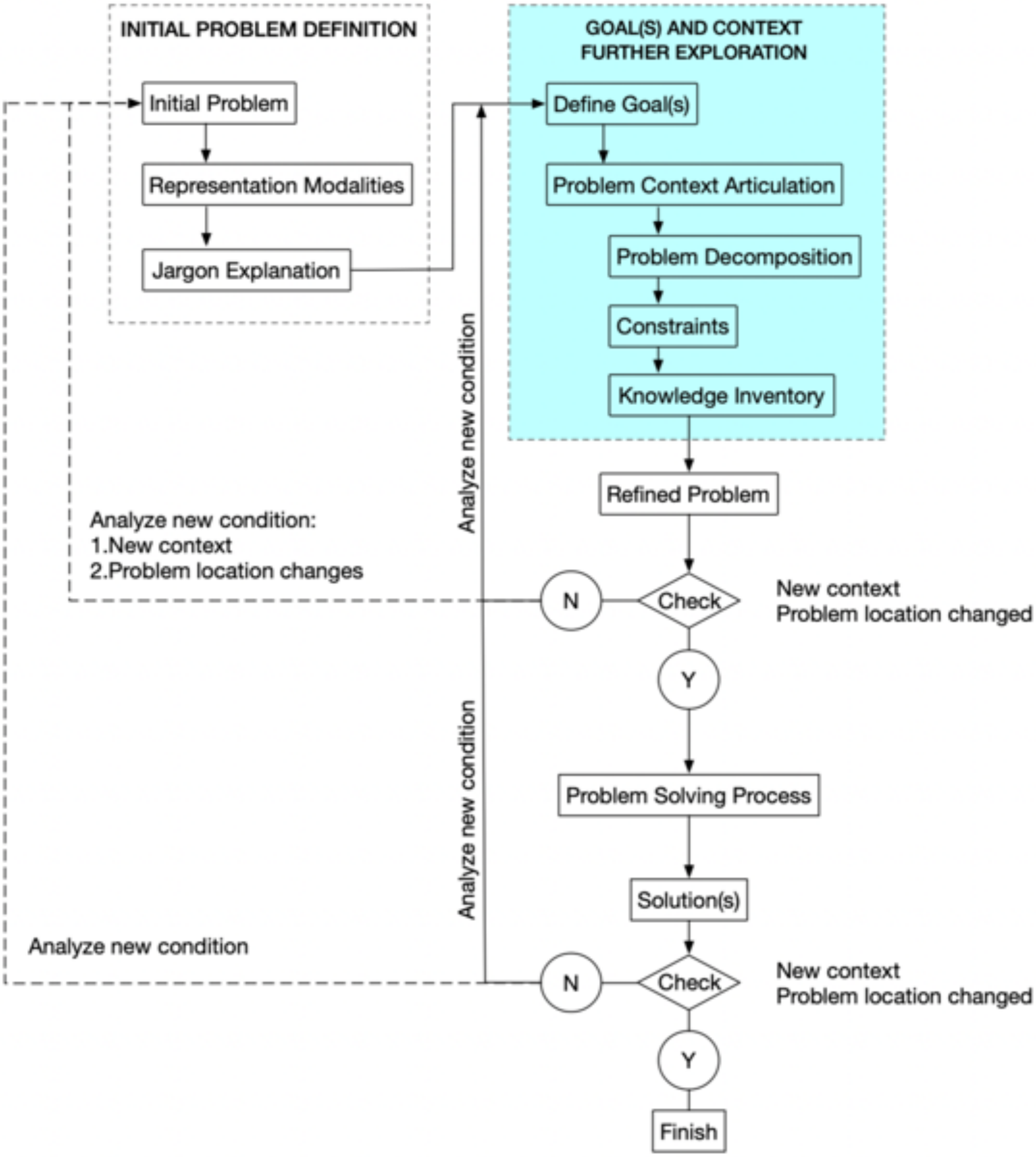


Figure 4.13 Goal and Context Further Exploration in the Problem Refinement Process

4.3.1 Define Value and Goals

According to the researchers from the NCAT, the specimen trimming wastes a lot of time and labor during the OT preparation. Researchers need to cut in a specific shape. They have to cut four times: two for sides (Figure 4.8), two for bottom and top (Figure 4.9). The first two trims need to have lines drawn on the cylinder specimen (Figure 4.7). The template originally asked to make is used to facilitate trimming. The researchers in NCAT use a previously created OT specimen to draw two lines (Figure 4.14). This method causes inaccurate cutting because the used OT specimen is trimmed by hand. Inaccurate line drawing causes one cylinder specimen to be wasted every four times cutting. So, the value can be defined: before the specimens are ready to be tested, they need to be cut in a specific shape; the lines drawn on them affect the accuracy of specimen shape which affect testing results (the critical fracture energy and the crack resistance index).

Figure 4.14 Using Used OT Specimen to Guide Drawing

4.3.2 Problem Context Articulate

In order to achieve this goal, the problem space needs to be developed by researchers and designers. This process involves problem decomposition, which helps divergent thinking and discovery constraints which helps confine the problem space. Knowledge inventory is added to the last step which is a complement of the problem.

4.3.2.1 Problem Decomposition

The initial problem can be decomposed as two parts: the drawing process should be quick and easy; cutting lines should be accurate (Figure 4.15). In this case, this process helps NCAT researchers to extend their problem space (Figure 3.10) instead of just making the used specimen as a measurement template (Figure 4.15).

Figure 4.15 Draw Lines and Trimming

4.3.2.2 Constraints

In this step, the NCAT researcher helps me (designer) to confine the problem space (Figure 3.11). According to the researchers, over three hundred dollars purchase needs to be tendered by the center. In that case the solution's budget is limited. The material needs to be durable and hard because they need to use the measurement template a lot of times. The constraint also includes the available tools I can use in the Industrial Design Department. The available machines are laser cutters, CNC machines and 3D printers.

4.4 Refined Problem

In consideration of all above, the refined problem is: create a measurement template to trim specimen pieces quickly and accurately by using hard material with available tools within a 300-

dollar budget.

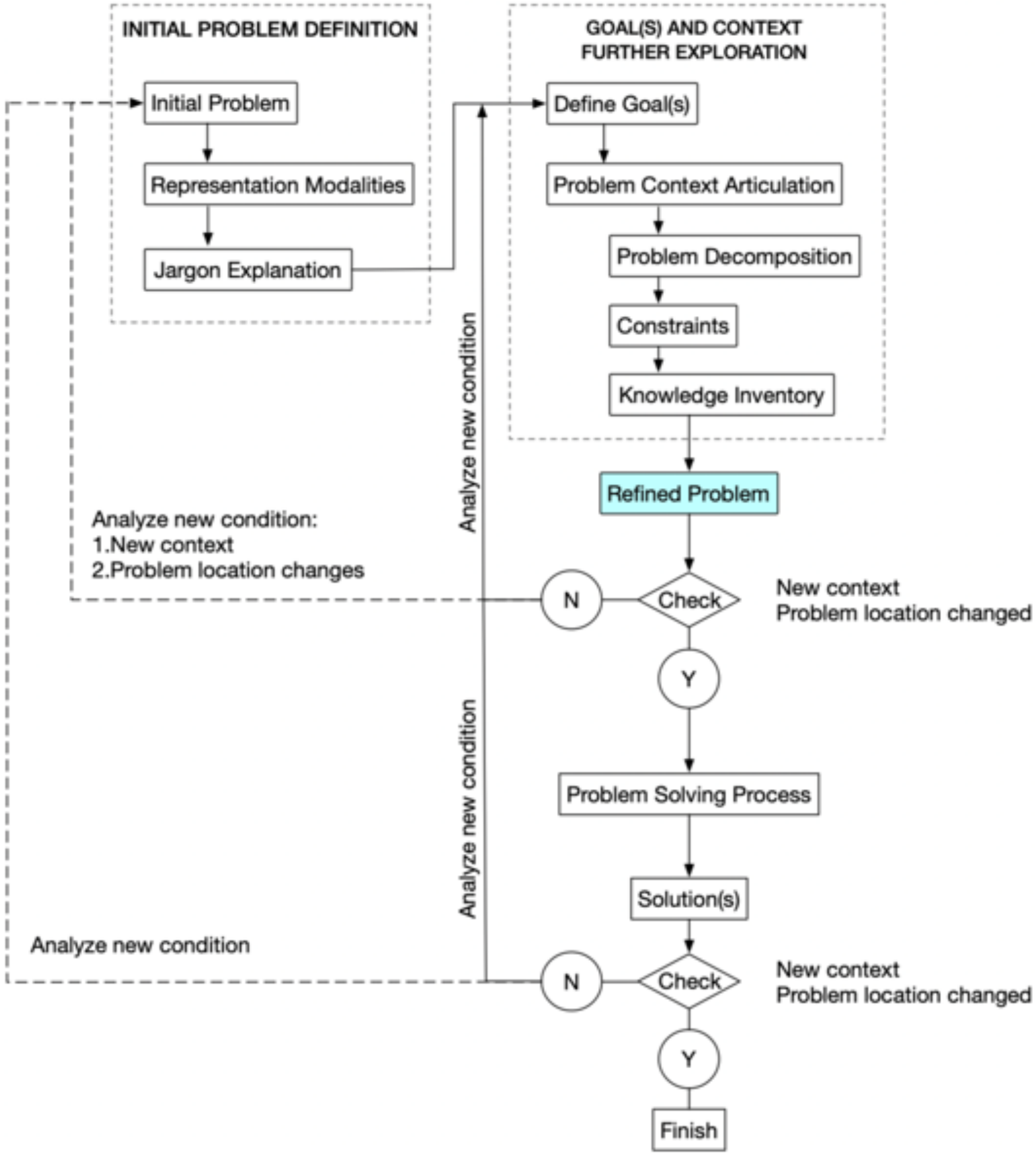


Figure 4.16 Refined Problem in the Problem Refinement Process

4.5 First Check Point before Problem Solving Process Starts

Before using the refined problem as a design brief, I check if there is a new context to be added. I find out that they actually use a short arc of the specimen as a calibration line (Figure 4.17). This is the new context found by the designer. Elongating the calibration line to increase the accuracy is beneficial.

Figure 4.17 Short Calibration Arc

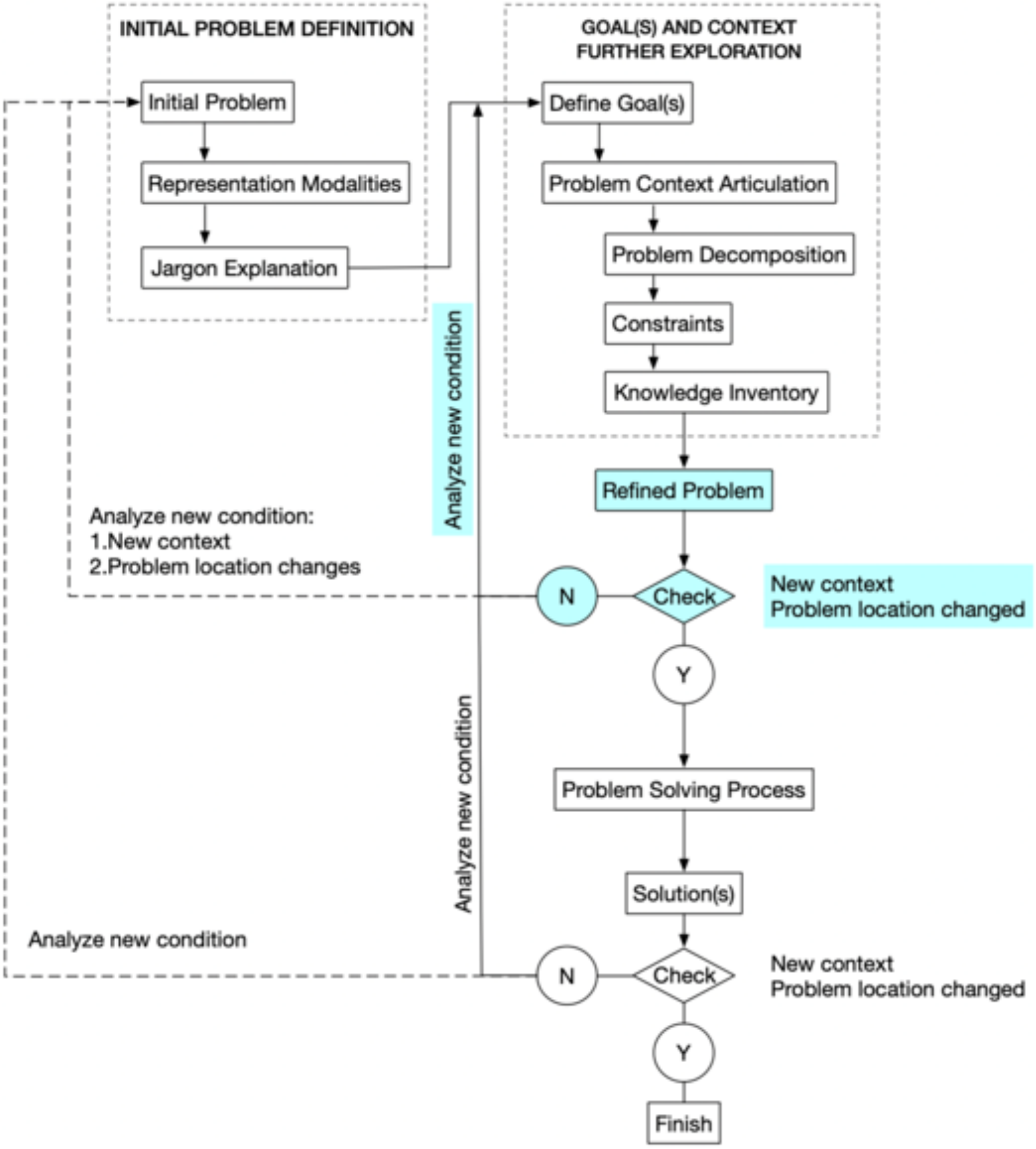


Figure 4.18 First Check Point in the Problem Refinement Process

4.6 Problem Solving Process and First Solution

Based on the refined problem, the first solution shows like Figure 4.20. I will not involve details about the problem-solving process in this thesis, but each solution needs to be explained. Firstly, I choose a laser cutter as a machine to make the measurement template, because the laser cutting machine is the most easily accessible machine in the department compared to the CNC machine, which does not open up to students' daily usage. Additionally, the laser cutter can support most material and cut through 1/2 inch thickness material. Secondly, the acrylic boards are used as the measurement template material because most of the rulers are made of this material and the transparent attributions can contribute to the measurement action. Comparing to the prices of different boards, the measurement template uses 1/12 inch thickness acrylic board.

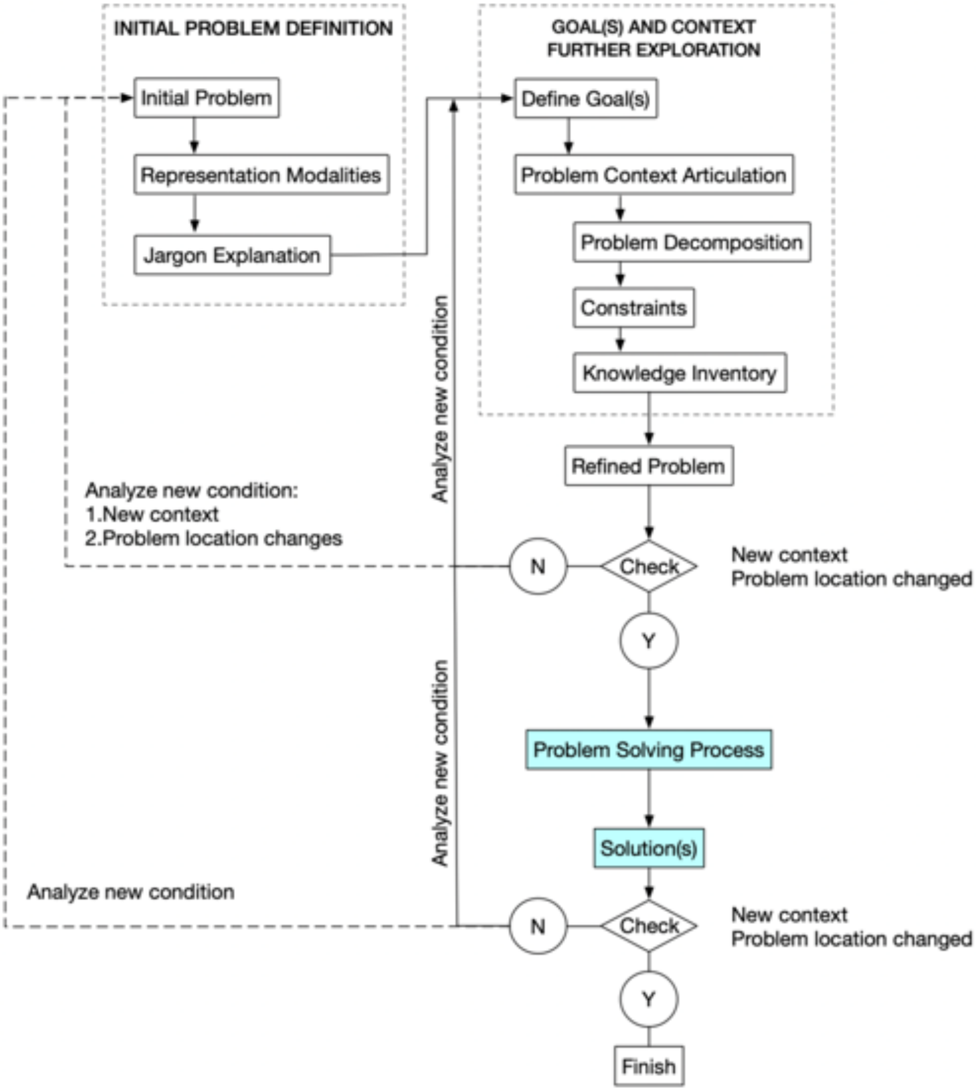


Figure 4.19 Problem Solving Process and First Solution in the Problem Refinement Process

To sum up, the solution includes these features:

1. Use 1/12 inch thick hard transparent acrylic to increase durability;
2. Use the laser cutter to cut an accurate template;

3. Increase the diameter of the measurement template to elongate the calibration line to increase the accuracy;

4. Etch two arcs to elongate the calibration line to increase the accuracy;

5. Cut out four extra corners to help drawing two lines through the specimen;

6. Cut a hole in the middle for leaving the space for the researcher to move or locate the measurement template easily;

7. Rounded corner to avoid uncomfortable use.

Figure 4.20 First Solution Based on Refined Problem

4.7 Second Check Point after Giving a Solution

After offering a solution to researchers in the NCAT, a check needs to be done by collecting usage information (Figure 4.21). According to researchers' feedback, this design is easy to use to draw the lines because of extra drawing space and elongated calibrating line. They used the template a lot, but the template is worn out, shown in Figure 4.22.

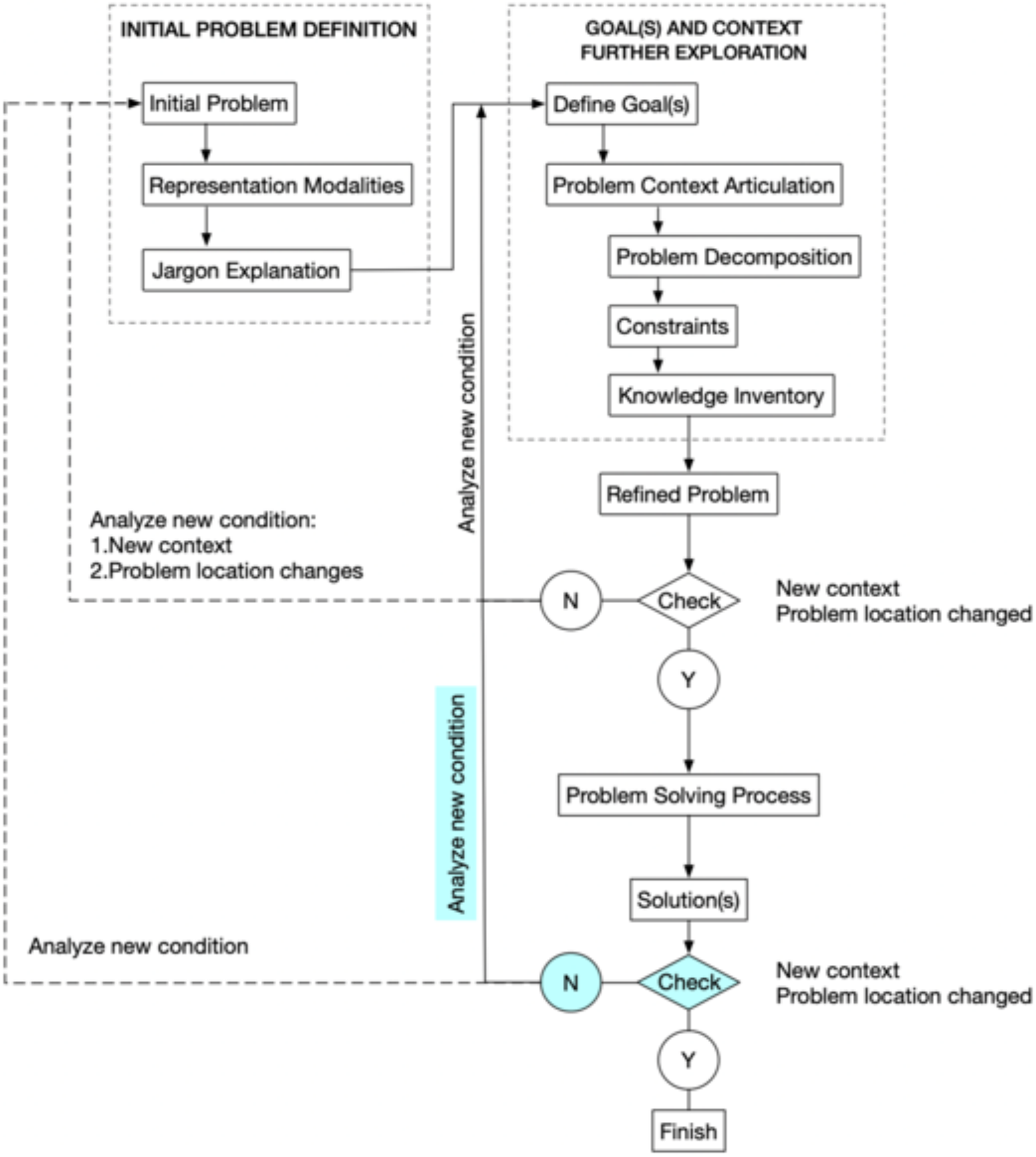


Figure 4.21 Second Check Point in the Problem Refinement Process

Figure 4.22 Worn-out Measurement Template

We can consider this as a new condition. With this new position of the problem, the strength of the acrylic plate is not enough because of the 1/12 inch thickness. So the problem needs to focus on making the material durable. The second solution creates an additional 0.22 inch additional acrylic layer to strengthen the template (Figure 4.23). Those two layers are connected by bolts and nuts. The two layers also divide the template to two functions: leading to draw the lines by the top layer and locating the template by the bottom layer. So, this design also has a benefit of quicker calibrating: researchers just need to snap the additional layer on the specimen without moving the measurement template around to locate.

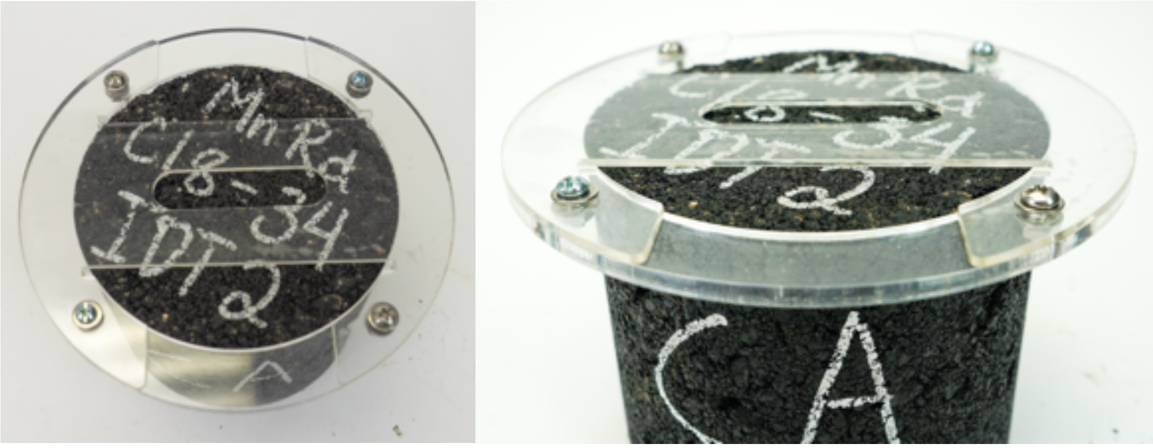


Figure 4.23 Second Solution with Addition Layer

4.8 Add New Things to Knowledge Inventory

After the second solution came out, a NCAT researcher gave me a standard of the ASTM Overlay Test (TxDOT, 2017). There is picture shown in Figure 4.24. It shows four metal snaps on the edge of measurement template. Even though the gap between snaps and the specimen as the picture shows and the discontinuous spaces of drawing line would affect the accuracy of trimming, the four snaps look easier to locate on the specimen than the second solution. As a new knowledge inventory, it helps the refined problem focus on locating the measurement template not so tightly.

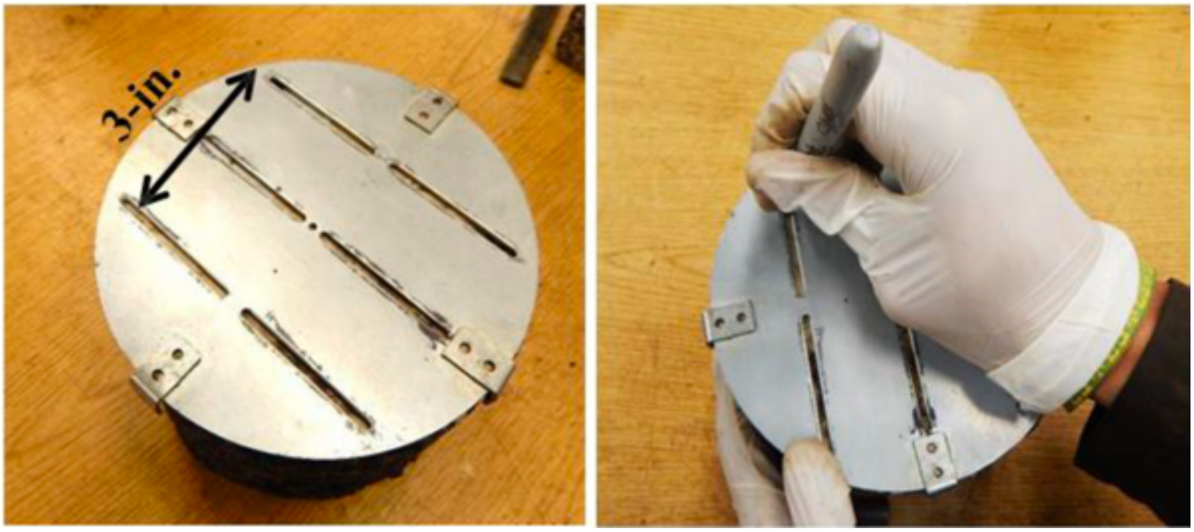


Figure 4.24 ASTM Measurement Template (TxDOT, 2017)

4.27).

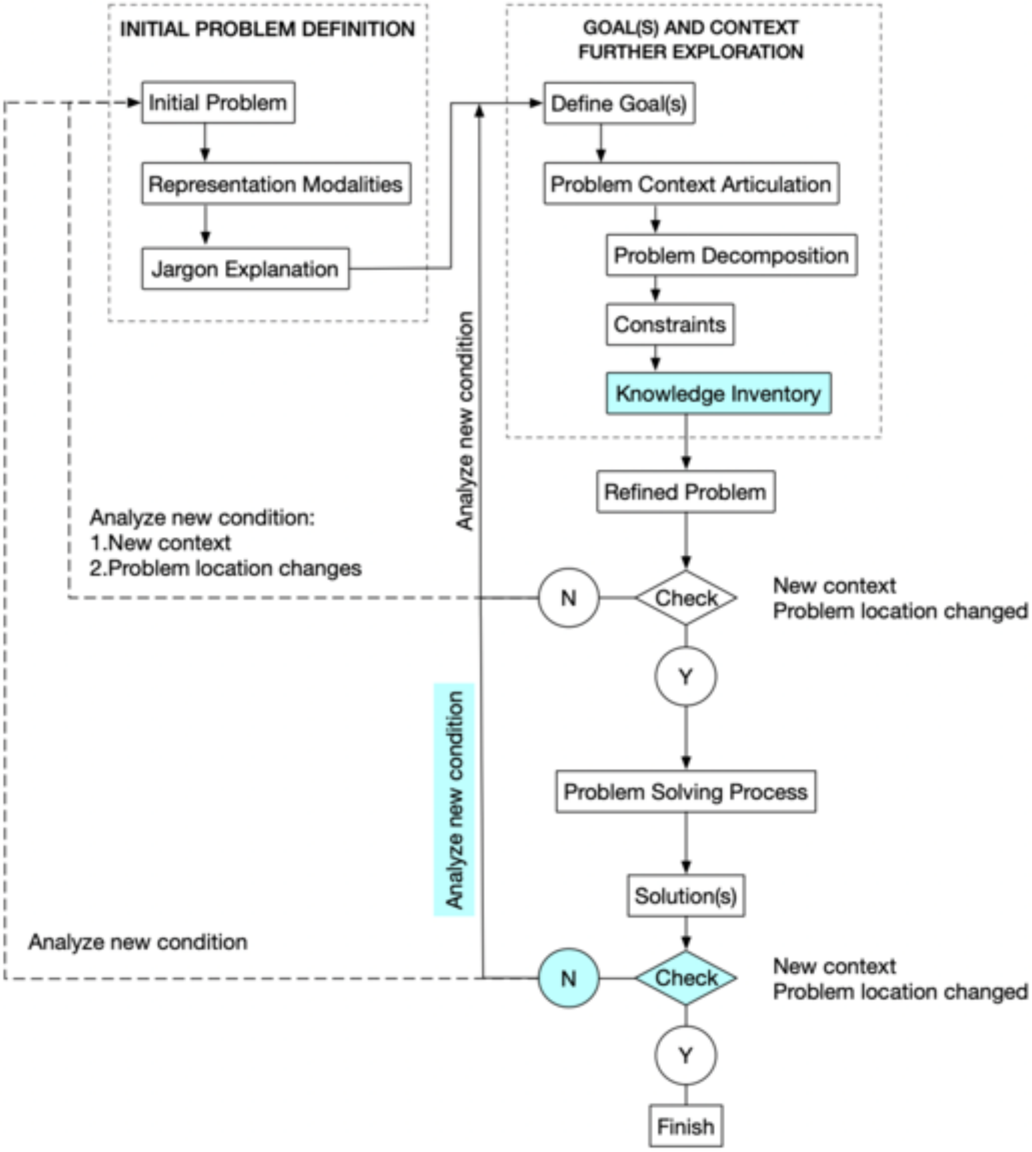


Figure 4.25 New Knowledge Inventory in the Problem Refinement Process

4.9 Final Delivery

In order to decrease friction between the bottom layer and specimen, I added a tooth shape on the additional layer to reduce the contact area (Figure 4.26). Tooth shape reduces the friction between the template and specimen which makes locating action easier. So far, there is no more new condition have developed. In that case the problem refinement process is finished (Figure 4.27).

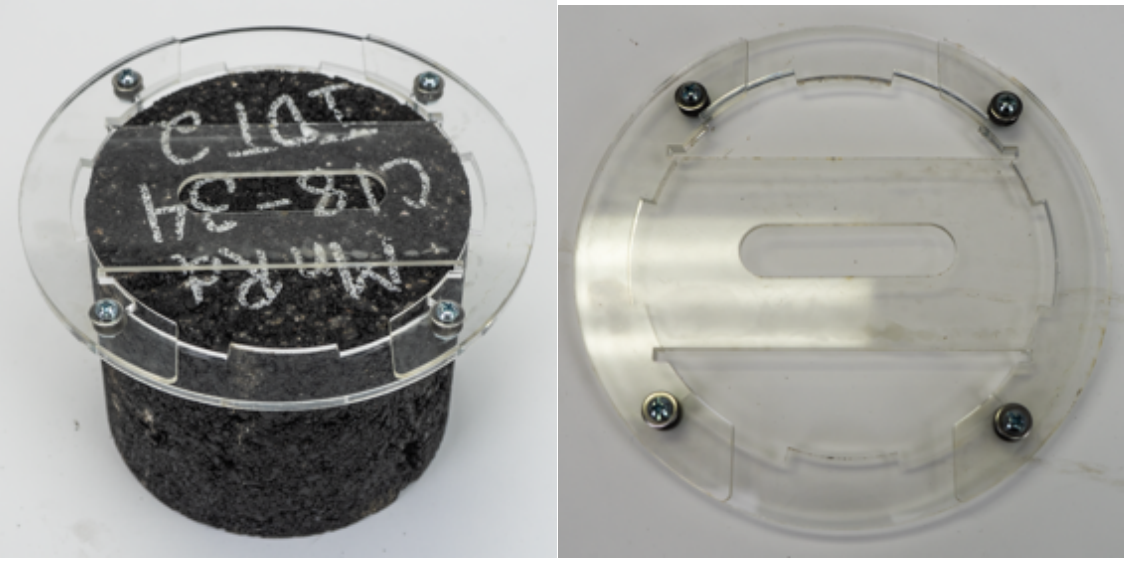


Figure 4.26 Final Delivery

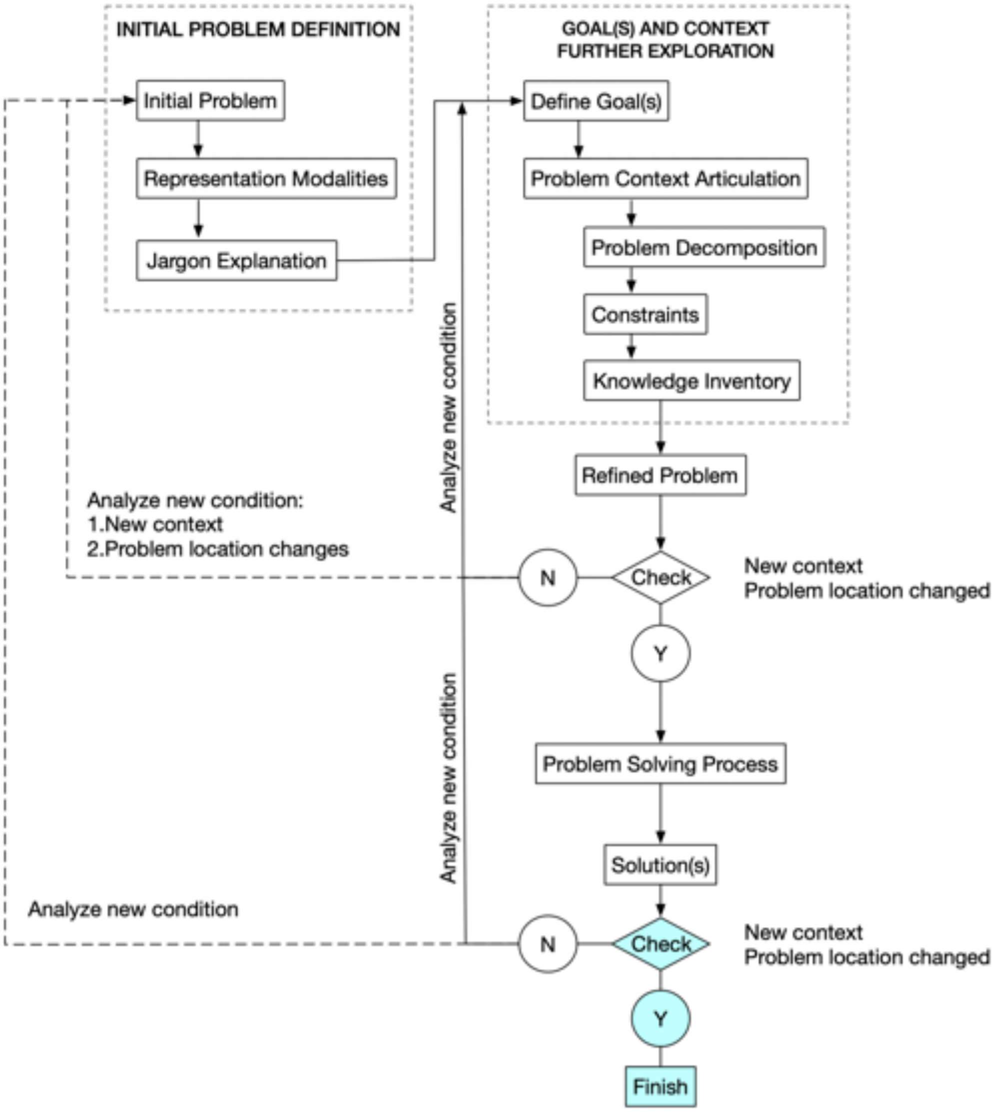


Figure 4.27 Last Check in the Problem Refinement Process

4.10 Summary

Since researchers do not know about design methods, the problem refinement process needs to be developed to introduce the problem to designers. Plus, the process can help researchers to know their problems clearly. Along with the fast pace of the world progression, the problem definition process will become more and more important because it decides whether the problem-solving process stays on the right track.

According to one NCAT researcher, the measurement template saves his time from 3 days to 1.5 days of trimming 300 pieces and wastes none instead of two asphalt pieces every 8 pieces during cutting process. With the latest template, the trimming experience has never been so easy.

Chapter 5 Conclusions

5.1 Summary of the Study

This thesis was intended to explore the opportunities for design collaboration and develop an approach to assist designers collaborating with scientific researchers towards the development of experimental tools and practices. Over the past decades, a lot of design theories and design methods have been proposed by design researchers, design theorists and design organizations. Some of them illustrate the difference of reasoning skills between design and science. Some of them offer different design methods fit for different industries. Some of them insist on the importance of openness, collaboration and cross-disciplinary for design. In the process, design becomes so irreplaceable, but has never received so much notice before.

However, design still has a great potential to help more people. Even though science is different from design, throughout the history, especially in the Ulm School of Design, designers tried to explain design by science. Similarly, design theories and methods can assist scientists.

This thesis focuses on a specific area of helping scientific researchers develop experimental tools and practices. By analyzing the logic of design and science, this thesis offers a way to broaden the problem space of researchers and confine this space of designers to create a suitable area to explore opportunities as much as possible. This thesis also provides specific steps to assist designers to help researchers develop experimental tools and practices by refining their problems, including creating the initial definition, defining the value / goal, and articulating the problem context. All of the steps are aimed at putting both of designers and researchers in the same picture before the problem-solving process really begin.

5.2 Suggestion for Future Studies

As indicated in the previous section, this approach needs to be demonstrated by more examples from different academic fields with design collaboration. Furthermore, this theory can be interpreted and applied in various areas. This research illustrates the way designers can collaborate with other people from other disciplines with different problem-solving ways.

Future research would build on this research by breaking boundaries between the logic of design and logics from other disciplines. By helping researchers build a refined problem together, designers can help others target the issue quickly and solving the right problems (Lockwood & Papke, 2017). Not only can this approach apply to the academic world, but also can help the business world. For example, when engineers tend to work with designers, this approach may help engineers extend their problem space and help the designer confine their problem space. As Figure 5.1 indicates, by refined problem statements, they can find the proper boundaries of the solution space.

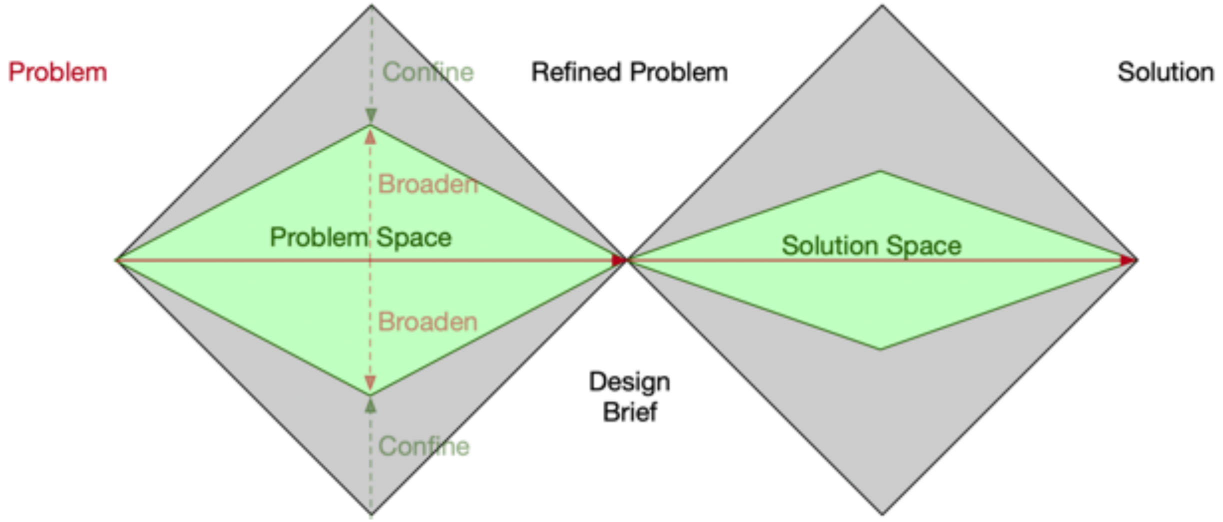


Figure 5.1 Problem Refinement Affect Design Solution Space

Future research would also help to interpret the design phenomenon. By applying the problem refinement processes to product design development process, compared to product redesign starting from goal and context, starting from the new initial definition may lead to disruptive innovation rather than iterative innovation. For example, after Jobs decided to kill the project of phone based on iPod, the Apple design team, which was led by Jony Ive began to focus on designing a brand-new multi-touch device. At the very early stages during design, they tried to establish the primary goals: how people feel about the product in a perceptual sense (Kahney, 2013). Due to this circumstance, Jobs described iPhone as ‘a breakthrough internet communications device’ (Isaacson, 2011). When they designed the iPhone, the initial definition is totally changed, leading Apple to create a whole new device instead of focusing on keeping the defined sub goal and articulating the context based on the current phone definition at that time, like Nokia. However, this theory may need further demonstration.

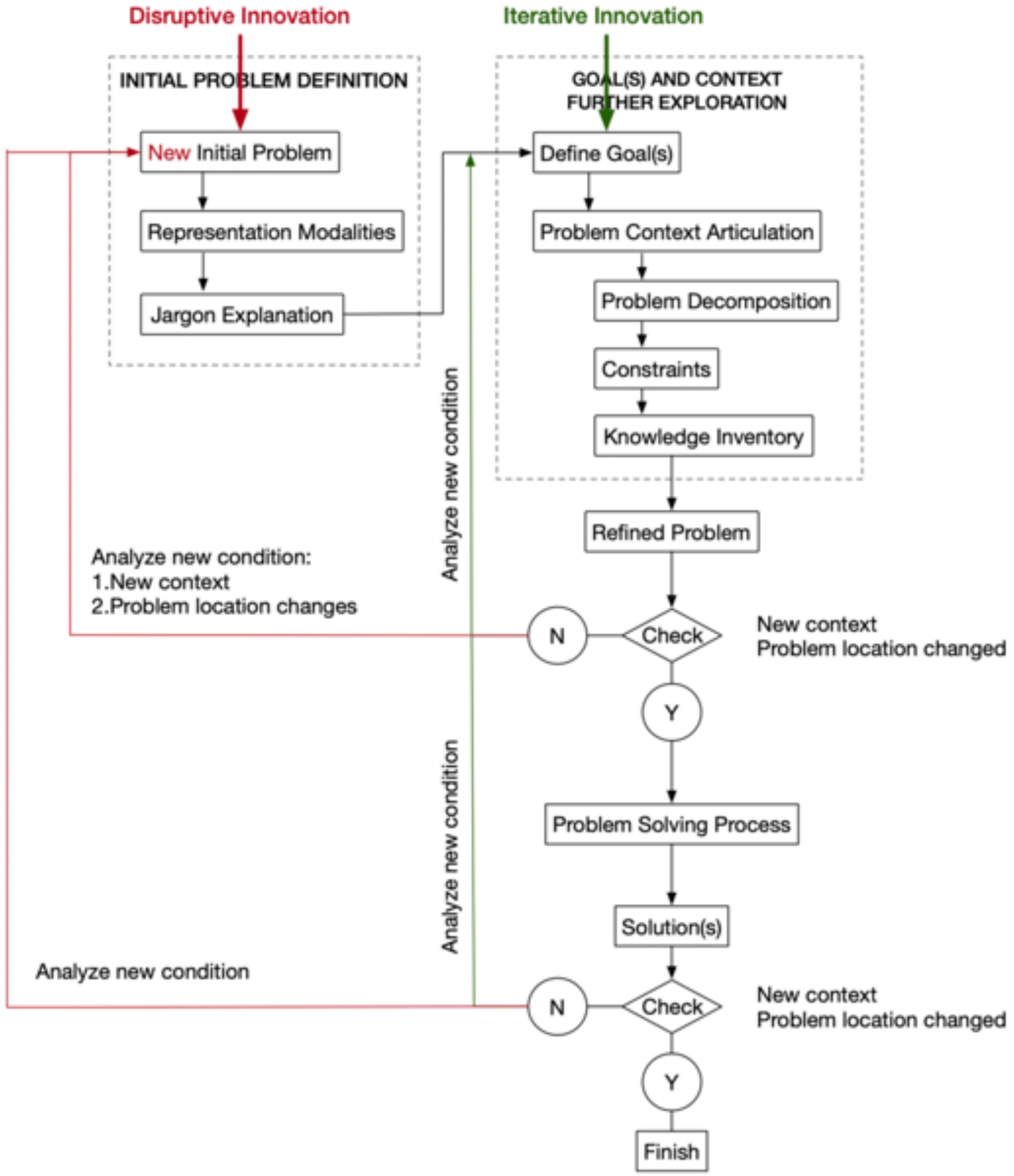


Figure 5.2 Disruptive Innovation and Iterative Innovation in the Problem Refinement Process

The main goal of future research is to solve questions by using research methodologies and design thinking methods not mentioned or used in this research and to identify how to approach the successful development of design collaboration between designers and researchers or other specialists.

Figure 5.3 Engineer’s Desk in the NCAT

This approach can also help engineers who work with researchers. There is an engineer works for the NCAT and help them solve problems. In the future, the engineer can use this approach to refine problem with researchers to understand the situation or context of the problem completely.

The importance of collaborative design development is revealed through this study and should be developed to recognize design problems and reduce the boundary of design collaboration, which can stimulate the application of design to the field it has never reached. In this way, design will become more and more important for helping academia.

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