JOURNAL of DESIGN THINKING

Deconstructing Visual Representation in Design: A Comprehensive Model of Sketching Activities in Design Process

Zhenyu Ma [1*]

[1] Graduate School of Creative Thinking for Social Innovation, Musashino Art University, Tokyo, Japan. Email: dcct21005bs@ct.musabi.ac.jp

*__Corresponding author:__ Zhenyu Ma

DOI: 10.22059/JDT.2024.380561.1128

Received: *8 August 2024,* ***Revised:*** *17 August 2024,* ***Accepted:*** *17 August 2024,* ***Available Online*** *from 17 August 2024.*

Abstract

Sketching is a fundamental design skill essential across various design disciplines. This study aims to develop a comprehensive model describing sketching activities throughout the design process, addressing the lack of unified frameworks in this area. Through a systematic review of existing sketch taxonomies, a generic classification framework was developed and integrated with the Uncertainty Driven Action (UDA) model. The resulting integrated model incorporates four main parameters: cognitive approach, intention, function, and complexity. It provides a structured approach to analyzing sketching behaviors across four design stages: investigation, exploration, explanation, and persuasion. Proof of concept, including prototype testing and scenario analysis, preliminarily demonstrated the model's feasibility, integrity, and accuracy in describing sketching activities. The proposed model bridges the gap between static sketch taxonomies and dynamic design process models, offering a theoretical foundation for understanding the role of sketches in design thinking and problem-solving. It has potential applications in design education, research, and tool development across various design fields, including product, service, and interaction design. This interdisciplinary approach contributes to a deeper understanding of design cognition and representation, potentially enhancing design teaching and practice. Future research directions include empirical validation, exploration of collaborative aspects, and integration with digital design tools.

Keywords

Design Sketch, Sketching Activity Model, Visual Representation, UDA Model, Design Process.

Introduction

Will the designers of the future be replaced by AI? Or can creative design solutions still emerge in an era overly reliant on AI? Against this potential backdrop, it is necessary to help designers acquire core design skills to maintain their ability to solve problems creatively. Sketching refers to the creation of rough or unfinished drawings that serve to explore and communicate design ideas quickly (Eris et al., 2014; Yang, 2008). It is considered a core skill and an essential part of the design process (Schembri et al., 2015; Dinar et al., 2015). The Uncertainty Driven Action (UDA) model, proposed by Cash and Kreye (2017), is a theoretical framework that links designer's uncertainty perception with their external design actions like information seeking, knowledge sharing and visual representation. It provides an integrated way to analyze the design process (Cash & Kreye 2018; Scrivener et al., 2000).

However, traditional design education often lacks emphasis on cultivating core design skills (such as freehand sketching, design ideation, design reflection, and visual communication skills), which in turn limits the creative potential of student designers, especially during the early stages of new product development (Ian, 2016). Among these, sketching is generally regarded as a fundamental design-related activity that is *impossible to separate* (Alcaide-Marzal et al., 2013). Although sketching is a quick, simple, and effective tool for design tasks and a common and frequent way of approaching design problems (Plimmer & Apperley, 2005), many people only see sketching as a means of visualization and rarely know how to use it as a tool for creative thinking (Leblanc, 2015).

Therefore, this study explores the mitigation of sketch inhibition (SI), a potential factor that adversely affects the cultivation of core design skills, with the aim of increasing the likelihood of successfully fostering these skills in higher education.

The focus on design sketch is not only because it is one of the core design skills but also because, as a discipline-specific method in design, it plays a crucial role in design education and practice, permeating almost all design disciplines. As research on sketching in design disciplines is currently fragmented, with contributions scattered across various fields, including cognition (Tovey, 1989; Schön & Wiggins, 1992), creativity (Hua et al., 2018; Verstijnen et al., 1998), reflective practice (Schön & Wiggins, 1992; Bilda & Demirkan, 2003), visual thinking and visual communication (Vistisen, 2015), human-computer interaction (Buxton, 2007), and digital technologies (Johnson et al., 2007).

SI is a complex phenomenon of individual, social, and technical inhibition types, or combinations thereof, proposed by Booth et al. (2016) and intensively researched and theorized by Thurlow (2019). These factors collectively contribute to design students' reluctance to sketch. Particularly, intellectual inhibition, an individual inhibition type, stems from a lack of understanding of the use and role of sketching in the design process, resulting in a reluctance to employ sketching during the design process, even with sufficient sketching skills. Furthermore, the rapid advancement of AI generative content (AIGC) technology fosters an unhealthy reliance on AI-integrated digital tools among design students in the early ideation stages of design, rendering the cause of technical inhibition increasingly important. This trend hinders the development of core design skills and exacerbates the widening gap between design education and industry practices (Yang et al., 2005; Kiernan & Ledwith, 2014).

Taxonomies, as fundamental knowledge organization tools, enable students to construct connections between knowledge, facilitating knowledge encoding, storage, and retrieval (Medin et al., 2000). Moreover, learning based on models and taxonomies that provide guiding theoretical frameworks offers important learning support for novices and enhances learning efficiency (Nievelstein et al., 2013). Recognizing the value of taxonomies and models in supporting learning and understanding, this study aims to bridge the theoretical gap in the lack of comprehensive models explaining sketching activities in the design process, thereby contributing to the alleviation of sketch inhibition, particularly in terms of intellectual issues.

Research on managing and mitigating this complex phenomenon of SI predominantly focuses on improving teaching methods for skill sets (Altenburger et al., 2022), with limited attention to addressing other issues. Despite extensive works on how to use sketching in design and its role, the function of sketching remains insufficiently understood (Yang, 2008; Purgathofer & Baumann, 2010). To address this research gap related to intellectual issues, this study aims to contribute theoretically and methodologically to improving intellectual issues.

Therefore, this study argues for a fundamental but comprehensive re-evaluation of the subject, beginning with the early step of understanding the kinds within the set of phenomena, namely developing its taxonomy (Simon, 1996). However, existing sketch taxonomies may not be practically applicable in design research. Reasons include:

1. Taxonomies used to explore the role of sketches in design are incomplete, lack coverage of different design domains (Goel, 1995; Pei et al., 2011; Eckert et al., 2012), and suffer from issues of completeness and precision due to a single criterion (Yang & Cham, 2006; Pei et al., 2011).

2. More students than expected struggle to differentiate between sketches in art and design disciplines. Despite much study and experience in sketching techniques and guidelines, the theoretical basis for teaching sketching in design education and understanding its role in the design process remains underdeveloped.

3. External representations such as sketches are scarcely included in design process models, leading to poor integrity of *internal cognition* and *external behavior* (Goel, 1995; Visser, 2006). As a result, theoretical models or frameworks for analyzing distributed sketching activities in design processes are noticeably insufficient.

Simultaneously, the lack of models describing sketching activities in the design process may be one reason why students' sketching behavior in the design process has become more intuitive. Therefore, this study aims to develop a comprehensive conceptual model that describes the complex and distributed sketching activities in the design process, which can help address and resolve the aforementioned issues. The development of such a model would not only aid in establishing rational thinking about students' sketching activities but also enable researchers and designers to gain a richer and deeper understanding of the use and role of design sketching, serving as a theoretical foundation and practical framework to support various design methods and sketching support tools. Section two details the structure of this paper, development methods, and research questions.

Methodology and Research Objectives

This research is not limited to specific disciplines such as interaction design, user experience design, and service design, but targets all design disciplines that involve sketching activities. Sketching is considered an indispensable part of the development of structures and processes.

Kranakis and Ferguson's (1994) findings emphasize the inherent similarity in conceptual development processes across disciplines, despite different manifestations. While disciplines may use different terminologies, the fundamental understanding of design behavior is similar (Crismond & Adams, 2012). Additionally, although research on sketch taxonomies has traditionally adopted a single-discipline approach (such as industrial design or engineering design), limiting the scope to a single domain may diminish the relevance of this research, as it is not confined to any specific design discipline.

Consequently, this research adopts a non-discipline specific approach, focusing on developing generic concepts involving sketching as a representational behavior, without being limited to any particular discipline.

This study aims to contribute to the SI improvement from the perspective of intellectual issues. Considering the current lack of theoretical foundations, such as taxonomies that comprehensively describe sketch classification, and discrete sketching activities within the design process across a wide range of design fields, the coordinated development of research and practice in this area has been hindered. Therefore, this study seeks to fill this gap by developing a generic sketch taxonomy and sketching activity model that can be used by both researchers and designers, thereby directly or indirectly contributing to the SI improvement from the intellectual standpoint.

1. *Research Questions and Objectives*

To lay a theoretical foundation for understanding the use and role of design sketches, thereby contributing to the alleviation of SI, this paper systematically explores and attempts to answer the following six research questions:

Q1. Is it feasible to select existing sketch classification criteria as the constituent elements of the proposed sketching activities model?

Q2. How effectively are the selected parameters describing various sketching actions in the design process?

Q3. What is the rationale for using the UDA model as the theoretical unit to describe sketching activities in the design process?

Q4. How can the generic sketch taxonomy be integrated with the UDA model, and what is the feasibility and integrity of this integration?

Q5. How can the integrity and accuracy of the integrated UDA model be validated, and what are the effects?

Q6. What are the future works and relation to SI research?

2. *Research Methodology*

This research employs systems theory to develop the comprehensive sketching activity model. Specifically, a mixed methodology approach is adopted, including a literature review, prototype development, qualitative analysis, and validation of the prototype. These methods are used cyclically to provide close integration and timely mutual confirmation (Figure 1).

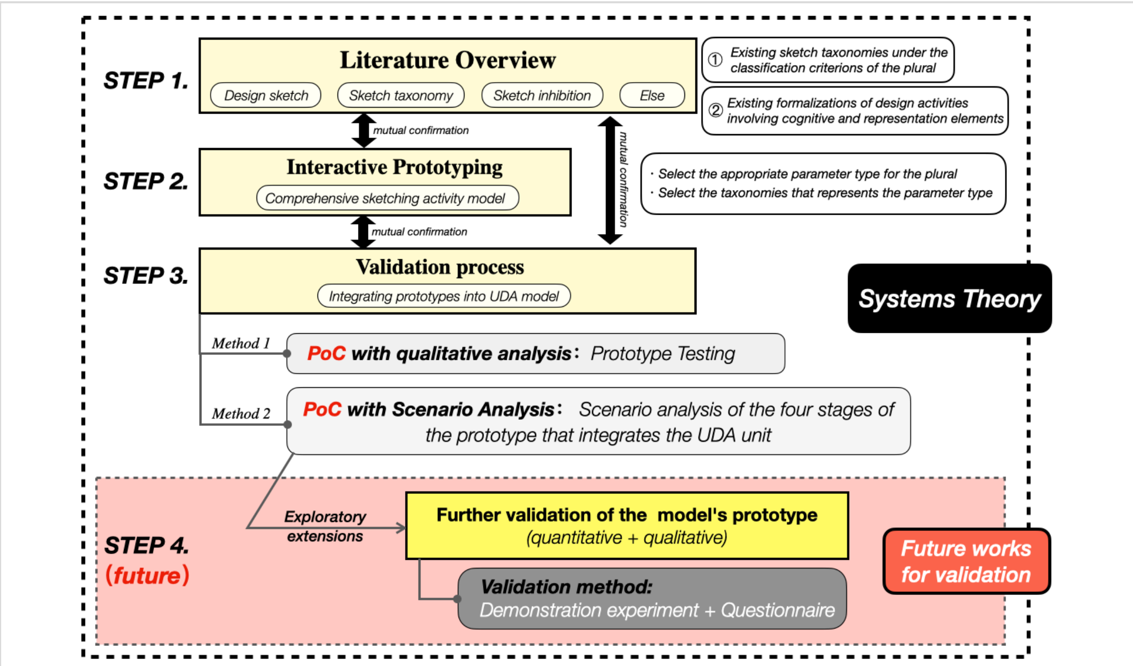

Figure 1: *The 4-step structure of research design (STEP 4 is not included in this study).*

Table 1 below describes in detail the purpose and specific work of the four steps represented in Figure 1.

Table 1: *Specific research design steps for this study.*

Step	Methods	Details	Corresponding Actions
1	*Objective Setting*	1. The aim is to develop a comprehensive model that explains various sketch activities within the design process. 2. Design the entire research process with an emphasis on ensuring the relevance of each step and the integrity of the research design.	Conduct literature reviews on "Design sketch, Sketch taxonomy, Sketch inhibition, Formalization of design activity", and subsequently determine the research objectives.
	Analysis of Existing sketch taxonomies	3. Collect literature on existing sketch taxonomies to comprehensively understand the field. 4. Organize and analyze existing sketch taxonomies according to classification criteria and stages of application, assessing their feasibility and accuracy.	Conduct qualitative analysis around the literature review of sketch taxonomy.
2	*Initial Prototype Development*	5. Based on the analysis of different classification criteria and the relationships between them, logically select complementary and integrated classification parameters. Identify the most representative and detailed alternative classifications from a systemic perspective for each parameter. 6. Integrate the selected taxonomies, systematically developing a comprehensive taxonomy prototype that includes revising or expanding the definitions of existing classifications.	Analyze the integrity, accuracy, and feasibility of the *representative taxonomies* obtained through the analysis.
	Theoretical analysis of prototypes	7. Systematically analyze the interactions and integration among the components of the prototype. 8. Introduce *reflection in/on action* as a framework for comparative analysis.	Contrast the above analysis results with the *reflection in/on action* framework to further evaluate its integrity and accuracy. (incorporating visualization into the analysis)
3	*Validate model integrated with UDA*	9. Integrate the comprehensive model prototype into the UDA model and qualitatively validate its feasibility, integrity, and integrity within the context of a simulated design process.	Integrate the prototype into the representation part of the UDA model and test the feasibility and accuracy of the prototype in a broader context.
	Prototype Validation with Scenario Analysis	10. Apply the UDA model integrated with the prototype across four scenarios, analyzing and testing in combination with uncertainty perception (UP) and other external representation actions.	Implement the proposed model in scenarios corresponding to the four sketching stages. Utilize the continuously updated UP for scenario analysis, testing its feasibility, integrity, and accuracy.
4	*(Future) Iteration and Optimization*	11. Plan to further adjust and optimize the prototype model based on the results of the PoC and prototype validation, gathering feedback, and conducting both quantitative and qualitative analyses.	Validate the model through demonstration experiments and qualitative questionnaires.

The cyclically employed methods are as follows:

1. Data from major databases (e.g., Google Scholar, Research Gate, ACM Library, Wiley, Science Direct), cross-domain literature overview on sketching, taxonomies, formalization, and inhibition, identifying research relevance and complementarity.

2. Based on the literature analysis, a prototype of a multi-criteria model capable of comprehensively explaining sketching activities in the design process is proposed and initially tested under systems theory through Proof of Concept (PoC). Comparison with single-criteria taxonomies, iterative updates to definitions, constituents, selected parameters, and relationships between sub classifications of the prototype.

3. The qualitatively tested prototype is further validated at each of the four stages by integrating it into the UDA model through simulated scenario analysis. In other words, the integrated UDA model's feasibility, integrity, accuracy, and other aspects are analyzed and evaluated.

Scenario analysis is a process of analyzing possible future events by considering alternative possible outcomes (Amer et al., 2013). In design research, scenario-based validation is often used to test the feasibility and effectiveness of a proposed method or framework by applying it to solve a typical design problem (Shammout et al., 2013). We chose scenario analysis to validate the proposed comprehensive sketching activity model because:

1) It allows us to simulate the real design process and sketching activities to test if the model can reasonably explain designers' sketching behaviors;

2) It helps identify potential issues of the model for further improvement by analyzing how it performs in dealing with a concrete design case (Zorriassatine et al., 2003).

Lecture Review of Existing Sketch Taxonomies

Many taxonomies have limitations in describing the whole design process and revealing the sub-functions of the design sketch, which is characterized by a lack of integrity and accuracy.

1. *Overview of Different Types of Sketch Taxonomies*

According to the literature, the design process is an *evolution of different kinds of representations* (Goel, 1995). Design sketches are classified by form (Tovey, 1989), intention (Olofsson & Siolen, 2005), and function (Ferguson, 1994; Lugt, 2005). They can also be differentiated by complexity and originate from various traditional design disciplines such as architecture (Fraser & Henmi, 1993), industrial design (Pei et al., 2011), and engineering design (McGown et al., 1998). Most taxonomies are tailored for early to mid-design stages. Pei developed a comprehensive taxonomic classification of design representations to clarify their role and improve communication between designers and engineers during new product development (Pei et al., 2011). Thurlow has found that many undergraduate students lack an understanding of their creative processes (Thurlow et al., 2018), leading to the process being lacking and in sightless.

However, due to their singular focus, current taxonomies might not effectively serve designers in design research and practice (Pei et al., 2011). Designers and researchers also find it difficult to refer to a single taxonomy that can involve and describe different types of sketches throughout the design process. Therefore, the lack of a generic sketch taxonomy to describe or map sketching behavior is considered a research gap. This study suggests that a single criteria interrelated and mutually exclusive taxonomy can be integrated into a unified system, thus providing a more appropriate theoretical basis for establishing a generic sketch taxonomy that can be applied in different fields and stages and contribute to filling the above gap.

Given the characteristics of sketches *speedy and tough*, this study's main scope of the generic sketch taxonomy is the early and mid-stage design process, such as investigation and definition, design conceptualization, and development. The author summarized and analyzed 16 sketch taxonomies that could be collected based on the classification criteria and originating disciplines (Table 2). This study's generic sketch taxonomy inherits the existing classifications' research findings and integrates and extends them.

The sketch taxonomies listed in Table 2 were selected from relevant design journals, conference proceedings, dissertations and books based on the following criteria:

1. it should be a classification system of sketches or sketching activities.

2. it should originate from or can be applied in a design field.

3. the classification criteria need to be clearly defined.

Taxonomies that are too specific for a particular design domain or incomplete in classification criteria were excluded.

2. *Parameter Selection and Cognition & Behavior Unit for Analysis*

As the elements constituting this generic taxonomy are limited to the existing classification criteria, this research does not discuss classifications beyond the existing parameter range. After reviewing and analyzing the existing classifications under various parameters, this study adopts the currently mainstream four classification criteria as the constituent parameters of the proposed taxonomy: *Cognitive Approach*, *Intention*, *Function*, and *Complexity*. The feasibility, integrity, and accuracy of these four parameters and their sub classifications are further analyzed and validated.

The use of classification alone may be insufficient to provide a reasonable and precise explanation of sketching actions within the complex design process, as external representations other than sketches are not considered. Although sketching activities are generally regarded as continuous, actual sketching activities are discrete, with other external representations and internal cognition occurring at the breakpoints.

This study considers the generic taxonomy as a vital element of the target sketching activity model prototype. Its use and role can be interpreted as the following iterative process steps:

1. The designer's comprehensive cognition and decision of the current situation (as input).

2. Based on the above cognitive decisions, appropriate sketching actions are performed through the following iterative 3-step process:

- Determine the intention for which sketching should be applied
- To achieve this intention, select the appropriate sketching function
- To utilize this function, choose the appropriate form of sketch

3. Select a specific sketching function and concrete form to reflect the mental image (idea) based on the specific intention (as output).

4. Engage in visual dialogue with the sketches.

Figure 2 (Part 1) illustrates this process as a single unit sample, while Figure 2 (Part 2) formalizes the combination of these units into a model representing the relationship between cognition and behavior, progressing the design activities.

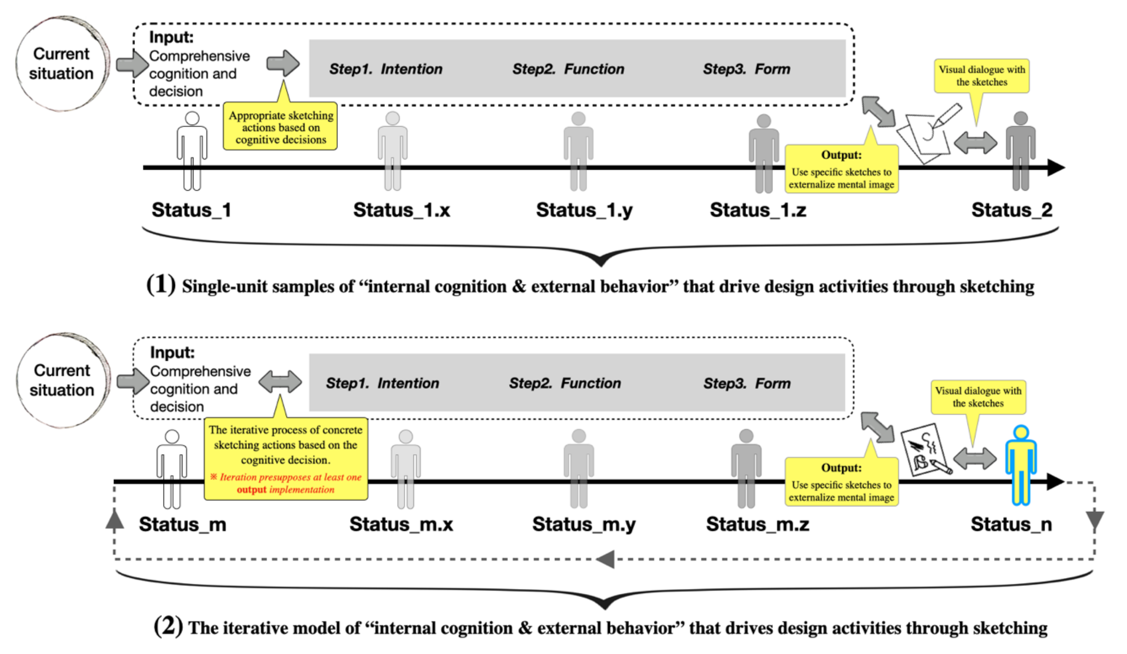

Figure 2: *Visualization steps for using the proposed generic sketch taxonomy as an action unit for sketching (0<x<y<z<10; m≥1, n≥2).*

Table 2: *Overview of existing sketch taxonomies according to various criteria and design disciplines.*

No.	Authors (Year)	Sub-classifications	Classification Criteria							Source disciplines
			Cognition Approach	*Intention*	*Function*	*Level of Complexity*	*Working Pattern*	*Form*	*Characteristics of Architectural Drawings*	
1	Tovey (1989)	Diagrammatic drawings; Ideas sketches; Concept drawings; Measured drawings.								Industrial Design
2	Radcliffe & Lee (1990)	Functional sketches; Geometric sketches; Pictorial sketches								Industrial Design; Engineering Design
3	Goodman & Porter (1992)	Orthographic projections; Axonometric drawings; Perspective drawings								Architecture
4	Ferguson (1994); Lugt (2005)	Thinking sketch; Talking sketch; Prescriptive sketch; Storing sketch								Engineering Design
5	Fraser & Henmi (1994)	Referential drawings; Diagrams; Design drawings; Presentation drawings; Visionary drawings								Architecture
6	Goel (1995)	Lateral transformations; Vertical transformations								Product Design
7	McGown et al. (1998)	Level 1; Level 2; Level 3; Level 4; Level 5								Engineering Design; Product Design
8	Ching (2003)	Multi-view drawings; Praline drawings; Perspective drawings								Architecture
9	Olofsson & Sjolen (2005)	Investigation Sketch; Explorative sketch; Explanatory sketch; Persuasive Sketch								Industrial Design
10	De Menezes (2005)	Orthogonal drawings; Axonometric drawings; Perspective drawings								Architecture
11	Pipes (2007)	Thematic sketch; Package-constrained sketch								Product Design
12	Yang (2008)	Dimensioned sketch; Non-Dimensioned sketch								Engineering Design
13	Huet et al. (2018)	Chronologically; Type of view; Subject								Product Design
14	Pei et al. (2011)	Personal sketch; Shared sketch; Persuasive sketch; Handover sketch								Industrial Design; Engineering Design
15	Lawson (2012)	Presentation drawings; Instruction drawings; Consultation drawings; Experiential drawings; Diagrams; Fabulous drawings; Proposition drawings; Calculation drawings								Architecture
16	Hua et al. (2018)	Working sketch; non-working sketch								Non discipline-specific

Design Process Model with Sketching Activity as a Constituent Element

This section reviews existing design process models to select an appropriate model that combines cognition and externalization to describe the design process. This is necessary to establish a suitable model foundation for describing discrete sketching activities in the design process, as well as to integrate the proposed generic sketch taxonomy into the selected model to obtain a target sketching activity model for validation.

1. *Formalization of Design Activity Considering Representation and Cognition*

Promoted by the British Design Council in 2005, the double diamond model, rooted in Bánáthy's (1996) and Cross's (2000) earlier work, illustrates design thinking as a balance of divergent and convergent thinking. This framework guides designers to expand their problem exploration before focusing on solutions, thereby managing project scope. Despite its effectiveness in scope management, it overlooks the impact of designer perceptions. Originating from Rowe's 1987 exploration, the Design Thinking (DT) model has evolved through studies in design, psychology, and education to identify how creative thinking ties with design activities. Researchers have developed various DT models, typically comprising 4 to 7 stages, to encapsulate the dynamic and iterative nature of design cognition (Plattner et al., 2010; Clune & Lockrey, 2014; Goodspeed et al., 2016). This approach emphasizes collaboration and feedback in the design process, although it underrepresents the link between cognition and external expression.

C-K theory (Hatchuel et al., 2004) delineates a dynamic interaction between concept (C) and knowledge (K) spaces, fundamental for materializing design ideas. It highlights the iterative design thinking process but leaves the specifics of cognitive process mechanisms and their externalization vague, posing challenges for practical implementation. Gero and Kannengiesser's model (2004) articulates the design process as recursive interactions among three spheres: external, interpreted, and intended, which collectively facilitate the transition from cognition to externalization. However, it lacks detail on operationalizing these interactions, particularly in translating cognitive behaviors into tangible outputs.

2. *Uncertainty Driven Action (UDA) Model to Conceptualize Design Activities*

Differing from the design process models described above, the UDA model (Cash & Kreye, 2017) employs uncertainty perception (UP) as a causal link between external behavior and internal cognition, providing a generic analytical framework for design activities and their progression (Figure 3). Section 4.2 concisely introduces the UDA model's components.

Information Action

Information action, defined as the handling and manipulating of data segments (Court, 1997), transforms data into knowledge to reduce uncertainty, a critical driver in the design process (Wilson, 1999). This includes designers' collection, recording, review, and archiving of data, which can be understood as the investigation of materials and definition of design problems in the design process.

Knowledge Sharing Action

Knowledge-sharing action, viewed as team communication in the design process, builds mutual understanding and enhances team consensus on concepts and solution, driven by the dynamics of uncertainty (Cash & Maier, 2016). Through this interaction, individual designers form new UP states, primarily by developing a shared understanding of concepts or solutions, and engaging in persuasion based on this understanding.

Representation Action

Representation actions, including design sketching and prototyping, deal with external information representations and their integration with internal reflections, which is crucial for enhancing team understanding and supporting design iterations (Evans, 2008).

Facilitated by *concept-knowledge* interactions, these actions serve as a conduit for updating UP around design artifacts, highlighting UP's role in driving representation activities.

Uncertainty Perception

UP serves as a metacognitive link across core design actions, intertwining internal cognition and external behavior to influence action decisions and sequences (Christensen & Ball, 2016).

It underpins the cognitive basis of information action, knowledge sharing, and representation action, continually evolving to guide the design process by bridging understanding, knowledge, perception, and activity progression.

A Generic Sketch Taxonomy Can be Adopted to Describe Sketching Actions in the whole Design Process

Based on the review and analysis in section three, this section selects the most generic and representative taxonomy from the four identified parameters and integrates them into a prototype model that comprehensively describes sketching activity.

1. *Key Elements Need to be Considered in the Design Process when Sketching*

First, Goel's taxonomy, unique for using cognition as a criterion, classifies sketches into lateral and vertical transformations, showcasing its general applicability (Goel, 1995). The concept of *transformation* in Goel's taxonomy represents the process of designers transitioning from one design state or representation to another during the design process. These transformations can be either lateral (between different design alternatives at the same level of abstraction) or vertical (between different levels of abstraction), with the aim of advancing the design process, optimizing the design solution.

Second, Olofsson and Sjolen (2005) categorized sketches by the designer's intention into four stages, roughly corresponding to the design stages. Combining cognitive and intention-based classification extends the cognitive approach to cover both early investigative stages and later stages of explanation and persuasion (Bedny & Karwowski, 2004).

Third, Sketches are widely differentiated into personal and shared types based on their function in practice. Distinguishing between Ferguson's (1994) *thinking* and *talking* sketches, and clarifying similarities and differences between Pei's (2010) *personal* and *shared* sketches, it's found that personal sketches can also be shared when individuals contemplate or modify others' sketches. Given Pei's detailed sub classifications and the broader applicability of *shared* over *talking*, this study adopts Pei et al.'s (2011) *personal* and *shared* sketch into a generic taxonomy combining cognition and intention above for a more realistic interpretation of sketch actions.

Lastly, this study selects a complexity-based classification for sketch forms that is versatile across all design stages. Thus, McGown's complexity-based classification of sketch forms in five levels (McGown et al., 1998) is more suitable than discipline-specific taxonomies from architecture (De Menezes, 2005), intention-based classifications in industrial and engineering fields (Tovey, 1989; David & Tat, 1990; Yang, 2008), or detailed classifications with specific requirements (Ching, 2003).

This study integrates these four parameters into a generic sketch taxonomy (Table 3) and visualizes it in Figures 3 and 4, indicating an iterative cycle among four stages and highlighting their sequential and interconnected nature.

2. *The Generic Sketch Taxonomy is Composed of Four Parameters*

After selecting the core elements, effective integration of the four parameters is required. This involves extending their original applied stages, harmonizing the scale among elements, and providing rational explanations to unify different classification criteria within a single model, as summarized in Table 3.

Table 3: *The four sketch taxonomies selected constitute the generic sketch taxonomy.*

Authors	Classifications	Categories	Definition
Goel (1995)	Cognitive approach	Lateral transformation	Movement is from one idea to a slightly different idea.
		Vertical transformation	Movement is from one idea to more detailed and exacting version of the same idea.
Olofsson & Sjölén (2005)	Designers' intention or need	Investigative sketch	Investigation and examination of the problem space during the early phase of unfolding a design problem.
		Exploratory sketch	Exploring and expressing design solutions for evaluation.
		Explanatory sketch	Communicating a clear concept to stakeholders outside the design situation.
		Persuasive sketch	Using sketches for rhetorical purposes, with less ambiguity and more details.
Pei et al. (2011)	Designers' functions	Personal sketch	Defining sketch, memory sketch, idea sketch, development sketch.
		Shared sketch	Explanatory sketch, prescriptive sketch, presentation sketch.
		Prescriptive sketch	Means that a concept has been chosen and drawings have been made to communicate certain elements.
		Storing sketch	Provides a means to save design ideas for future use.
McGown et al. (1998)	Complexity of the sketch	Level 1	A monochrome line drawing without annotations or shading.
		Level 2	Monochrome sketch with motion arrows and/or annotations or shading.
		Level 3	Monochrome sketch with annotations and shading.
		Level 4	Level 3 sketch with extensive use of shading and color.
		Level 5	A realistic Level 4 sketch that uses digital software.

By systematically refining the definitions and applications of these parameters, the generic taxonomy becomes more feasible, ensuring better cohesion and integrity among them.

Prototype of the Sketching Activity Model Integrated with the UDA Model

In this study, we adopted three criteria to validate the proposed generic sketching activity model: feasibility, integrity, and accuracy.

1. Feasibility refers to whether the model is logically sound and can be applied to analyze sketching activities in practice.

2. Integrity means the components within the model are coherent and consistent with each other without contradiction.

3. Accuracy indicates the extent to which the model precisely captures and explains designers' actual sketching behaviors in the design process.

These criteria were selected because they cover the key aspects that need to be considered when evaluating a theoretical model, i.e., its theoretical soundness, internal consistency, and explanatory power. Only a model that meets these criteria can be deemed valid and useful for its intended purpose.

Following a preliminary analysis, this section incorporates the qualitatively tested generic sketch taxonomy as a specific representation action of external behaviour within the UDA model for further PoC. The validation criteria include this integrated UDA model's feasibility, integrity, and accuracy.

Integrity is assessed by analyzing and testing the integrated UDA model's cognition aspect within the framework of reflection-in-action and reflection-on-action. Integrity and accuracy are also evaluated by examining whether the model's parameter combinations, once integrated with the UDA unit, maintain logical consistency in a broader context and whether they can accurately interpret sketching actions under various conditions.

Finally, feasibility is inferred based on evaluating integrity and accuracy, and a comprehensive assessment of the integrated framework is conducted.

1. *Relationship between Reflection in Action/on Action and the 4 Parameters Describing the Sketch Classifications*

Reflection is a crucial part of the design process (Schön & DeSanctis, 1986). Designers reflect both during (reflection-in-action) and after (reflection-on-action) sketching to examine and respond to the design situation (Valkenburg & Dorst, 1998). Reflection in and on sketching action enables designers to:

1. Understand the problem and explore solution spaces (Goldschmidt, 1991)

2. Evaluate and improve design ideas (Suwa et al., 2000)

3. Communicate and discuss with others (Schön, 1992).

Therefore, a comprehensive sketching activity model should well accommodate and explain designers' reflection behaviors in relation to sketching. By integrating the reflection in/on action framework into the evaluation (Adams et al., 2003), authors can test if the proposed model adequately captures this important characteristic of sketching activities in the design process.

Reflection-in-action is the process of reflecting without interrupting the action, thinking about what one is doing while doing it, thereby influencing further behavior. This can be undertaken individually during design or by design teams working together (Schön & DeSanctis, 1986).

Reflection-on-action is a calmer, post-event reflection, where designers pause to reconsider what they have done, exploring their understanding of the task at hand. It facilitates *stepping out of the design process* and can be conducted by individuals, teams, or with a facilitator's assistance (Stumpf & McDonnell, 2002).

To support structured reflection in the design process, Reymen developed a multidisciplinary framework (Reymen, 2001). Despite the complexity of reflection in action/on action within design activities, the basis for reflection involving sketch action remains singular and ambiguous. This study proposes four parameters for integrating analysis of reflection in action/on action within sketch activity, further exploring theoretical interpretation for sketching in design (Table 4). These include cognition approach reflections both in and on action, necessitating direction judgment either during or post-activity.

Table 4: *Detailed description of the harmonization and integration of the four parameters constituting the generic sketch taxonomy ("Intention" is considered as the main parameter, while the other three parameters "cognitive approach", "function", "complexity" is considered as secondary parameters.).*

No.	Intention (4 stages) / Criteria	**Investigative**	**Exploratory**	**Explanatory**	**Persuasive**
		Investigate the design context and problems using sketches; manifested as recording and summarizing with sketches.	*Explore tentative design problems using sketches; manifested as visualizing ideas through sketches.*	*Explain provisional design concepts using sketches; manifested as utilizing sketches as visual media to aid explanation.*	*Persuade stakeholders of design concepts; manifested as utilizing sketches as visual media to assist persuasion.*
1	*Cognitive Approach*	Cognitive shifts in specific investigative direction when collecting information in order to identify design issues.	In exploring a solution to a design problem, the exploratory direction in which the idea or concept needs to be changed (e.g., lateral or vertical) is determined based on cognitive activity.	Utilize concepts and sketches from previous stages for explanation to other stakeholders, and refine the understanding of the sketch-based concepts based on received feedback.	Employ concepts and sketches from earlier stages to persuade stakeholders, and adjust the cognitive direction of sketch-based concepts based on their feedback.
2	*Function* *(personal, shared)*	Investigative sketches can be either personal or shared, involving self-directed data investigation or collaborative investigation and discussion with others.	The exploration with sketches includes both two main forms of individual exploration and exploration with others by the means of talking or collaborative working.	As the process of using sketches to explain concepts is a shared form, the function of sketching under the explanatory intention almost can only be shared.	Since the process of using sketches to persuade regarding concepts is also a shared form, the function of sketching under the persuasive intention can almost only be shared.
3	*Complexity*	The sketches to record and summarize the data are generally level 1 and 2.	The sketches for visual exploration of ideas are more diverse, ranging from level 1, 2, 3, and even 4.	Sketches for explaining concepts require a higher level, usually level 2 to 4, and sometimes even level 5.	Compared to the explanatory stage, the complexity here is relatively higher, usually at level 4 to 5, and occasionally at level 3

Additionally, the intention and function required during sketching are applied to reflection in and on action. In reflection-in-action, designers continuously reflect on whether the current design situation aligns with or deviates from their intended purpose (e.g., investigation, exploration, explanation, persuasion).

In reflection-on-action, a cognitive approach is first applied for retrospective reflection on the design's intention and function of sketches based on the current state. This process aids in determining whether to continue refining or modifying the design or to conclude the loop for iteration, influencing the complexity of sketches in the next *reflection in action/on action* cycle. Consequently, reflecting on complexity is most appropriately conducted during reflection-on-action, serving as both an outcome of reflecting on a mix of cognitive, intention, and function parameters and a crucial indicator for identifying new cycle occurrences.

For clarity, refer to the revised UDA model incorporating both the reflection framework and the generic sketch taxonomy (Figure 3). The aforementioned analysis and integration preliminarily align the selected four parameters with the potential for integration into the *reflection in action/on action* framework, and logically analyze how they work together cyclically in the reflection framework.

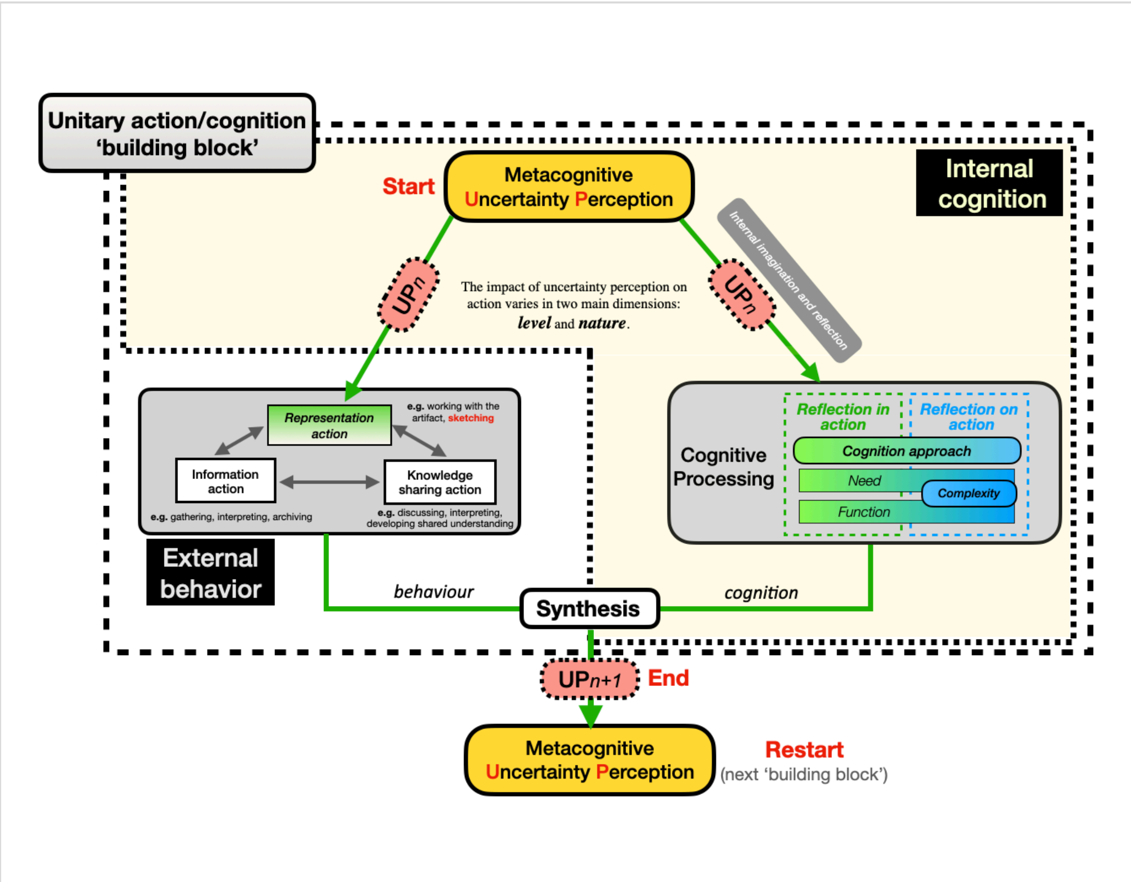

Figure 3: *The visualization prototype integrates the "reflection in action/on action" framework with the generic sketch taxonomy into the UDA model (i.e., the prototype of the sketching activity model).*

2. *Integration of Generic Sketch Taxonomy into the UDA Model*

It provides a coherent way to describe the design process across contexts and over time. Integrating the proposed taxonomy of sketching activities into the UDA model has two main benefits:

1. It allows the existing sketch taxonomies with different criteria to be applied and tested comprehensively in a broader framework of design process rather than being isolated;

2. It enriches the representation action part of the UDA model with a more detailed and structured explanation of sketching behaviors.

The integrated model above has several features:

1. The iterative progression between 4 sketching intentions can be seen as 4 certain loop combinations, which are constituted by the combinations of 3 UDA core actions under specific criteria;

2. Due to the nature of sketching in the design process, some sketching intentions may involve more frequent and dynamic shifting of loop combinations between UDA core actions than others.

Section 5.1 identified four parameters as generic criteria for describing sketch actions in design process (Olofsson & Siolen, 2005). Based on this classification method, this section focuses on integrating the generic sketch taxonomy with the UDA model.

In the UDA model, the designer addresses changes in perceived uncertainty through one of three actions with cognitive processing. The four stages of the generic sketch taxonomy represent a progression of design process objectives, with each stage forming through multiple iterations of UDA unit combinations.

Integrating this static framework (generic sketch taxonomy) for sketching activity with the UDA model clarifies and partially predicts the relationships between cognition and behavior. Although a comprehensive analysis of cognition activities may still be elusive, the integrated UDA model prototype helps explain design processes involving sketch-related representation actions.

Furthermore, integrating the generic sketch taxonomy with the UDA model, which includes two other core actions, allows the taxonomy, which primarily focuses on sketching activities, to be incorporated and tested within a model describing the design process. This integration provides an opportunity to explain discrete sketching activities coherently throughout the design process.

Sketching can thus be divided into four discrete stages (Olofsson & Siolen, 2005), symbolizing the evolving intentions of sketch usage as the design process progresses. When iteration of the design object is necessary, changes in the intentions of sketching may occur, transitioning from the intentions of later stages back to those of earlier stages to facilitate iterative progression.

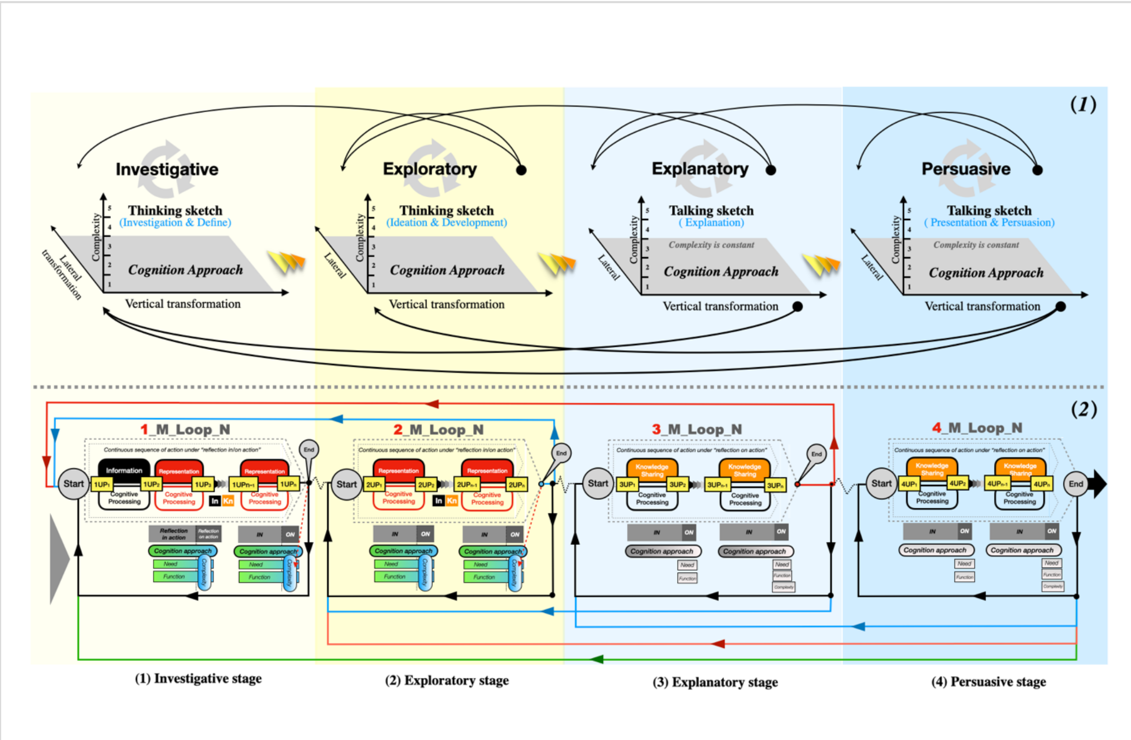

Figure 4: *A generic sketch taxonomy composed of four stages; 1. 4-stage visualization of a locally discrete yet holistically coherent generic sketch taxonomy (arrows denote iterative relationships within and between stages); 2. Possible progression of UDA unit combinations integrating the generic sketch taxonomy from upper across four stages (arrows denote iterative relationships within and between stages).*

Figure 4 illustrates the generic sketch taxonomy's four stages in the upper part 1. The lower part 2 displays the UDA progression's unit combinations within each stage, alongside a schematic of the iterative relationships between stages indicated by arrows. This figure shows the stages as discrete in isolation but linearly coherent overall. Additionally, as a crucial part of PoC, section 7 analyzes the model's four stages across different simulated scenarios, providing preliminary validation of its feasibility and accuracy.

PoC to Validate the Integrated Sketching Activity Model with UDA

This section delves into a scenario analysis of PoC for the sketching activity model integrated with the UDA model. It specifically predefines a method for logically grouping a series of continuously updated UPs based on their level and nature, represented in Loops.

1. *Basic Structure and Approaches to the Progression of the Integrated Model*

The study defines the progression of UPs within the UDA unit under the consistent directions of investigation, exploration, or explanation as a finite loop. The condition for concluding a loop at any stage is defined by a significant transformation in the design direction of the object (i.e., a *restart*). The number of uninterrupted Loops within the same stage is denoted by an integer M ($M \geq 0$).

Within the same loop, several vertical or lateral transformations related to the object, or its design direction occur to progress UPs. Each UP update represents the execution of a UDA unit, with the number of these executions designated as an integer N ($N \geq 0$). Thus, *M_Loop_N* represents a specific point within a sketching stage.

Table 5: *A summary of the four stages in the model integrated with UDA, including the constituent UDA elements, the operation mode of the loops composed of UDA elements, and the termination criteria for each loop in each stage.*

No.	Stage	Description	Constitutive actions	Features of the loop	The standard for determining the end of one loop
1_M_Loop _N (X/Y)	Investigative	Conduct the research necessary to define the design problem (Sketch is a means of recording and summarizing). ※Lateral transformation refers to changes in the direction of the investigation; ※Vertical transformation refers to in-depth development in the same direction of investigation.	• Information ([In]) • Knowledge sharing ([K]) • Representation ([R])	**In one Loop,** (1) Start is [In] and end can be any three actions. (2) There are three actions exist in the loop. These possibilities lead to iteration into the next loop, signifying a somewhat updated direction for investigating and defining the design problem.	**Criteria for the end of one loop** - When there is a significant change of direction in the investigation of the design problem **Criteria for the completion of the stage** - When it is decided that UP should move to the next or previous design stages (depending on the designer).
2_M_Loop _N (X/Y)	Exploratory	Explore solutions to design issues defined in the previous stage through sketch	• Knowledge sharing ([K]) • Representation ([R])	**In one Loop,** (1) Start is [R] and end can be any two actions. (2) There are two actions exist in the loop.	- Loop Restart (c) occurs - When UP is considered ready to move to the next or previous stage (depending on the designer)
3_M_Loop _N (X/Y)	Explanatory	Using the concept sketches developed in the previous stages as a medium, explain to the stakeholders	• Knowledge sharing ([K]) • Representation ([R])	**In one Loop,** basically only [K] is existed, but [In] may be included depending on the situation	**When continuous explanation ends** - Active: judgment of others or self-judgment - Passive: until there is nothing to explain (temporarily saturated)
4_M_Loop _N (X/Y)	Persuasive	Present and persuade external stakeholders using concept sketches that have been iteratively developed and confirmed in the previous several stages	• Knowledge sharing ([K]) • Representation ([R])	**In one Loop,** there is only [K] unless there is an extreme case.	**When continuous persuasion ends** - Active: judgment of others or self-judgment - Passive: until there is no one to persuade (temporarily saturated)

To enhance the precision of the expression for different stages, we extended it by introducing the integer K at the beginning, representing the four stages ($1 \leq K \leq 4$; 1: investigative; 2: exploratory; 3: explanatory; 4: persuasive).

Once the design activity begins, sketching activities alternate repeatedly among the four stages. *X* denotes the current number of times the intention of the same stage is being experienced (X≥0, X≤Y), while the integer *Y* indicates the total number of iterations experienced in a particular stage (Y≥0), incremented when moving to other stages or concluding the design activity in the current stage. The overall expression can be represented as *K_M_Loop_N (X/Y)*.

The composition and characteristics of loops vary slightly across different stages. Table 5 summarizes and explains the definition of loops, constitutive actions, characteristics, and criteria for loops that conclude within each stage, offering a structured approach to analyzing the progression of the integrated model.

2. *Scenario Analysis of Representation Actions across the Four Stages of the Comprehensive Sketching Activity Model*

This section conducts a simulated scenario analysis for the four distinct stages of the integrated model.

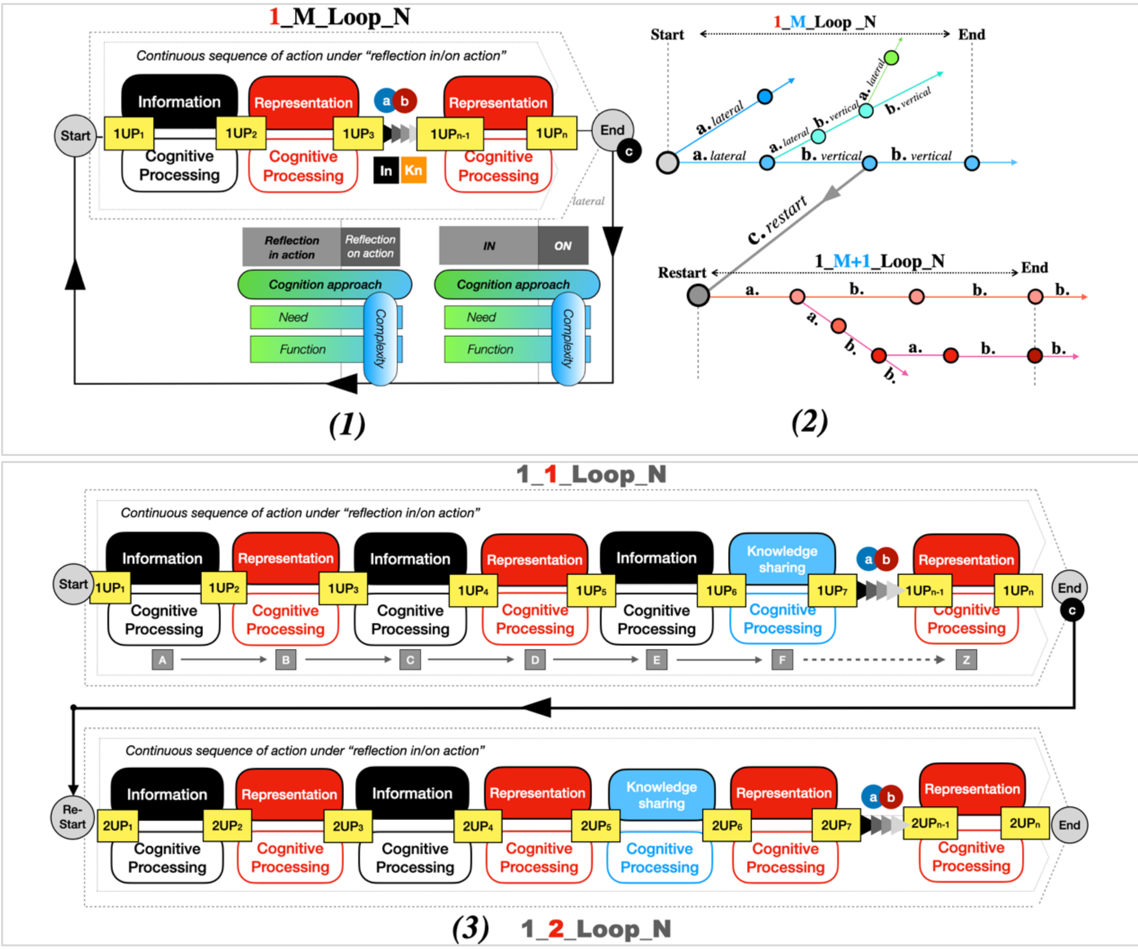

Figure 5: *The integrated sketching activity model for the investigative stage, composed of UDA units and the generic sketch taxonomy embedded with the reflection in action/on action framework; 1. A loop in the investigative stage represented by the progression of the model through the combination of UDA units; 2. A tree diagram illustrating the three possible options when UDA units are updated and generate a new UP; 3. The sample of two consecutive loops composed of UDA units in the investigative stage.*

Each stage involves information actions, knowledge sharing actions, representation actions, and cognitive processing, adapted to be suitable for expression through Goel's cognitive approach sub classifications. Thus, in addition to *lateral* (a) and *vertical* (b) cognitive transformation, consideration is given to iterative cognitive transformations when significant shifts occur. Here, loops serve as the units for iteration. A *restart* (c) is triggered when the designer determines a change in the current direction of investigation or exploration is necessary, initiating a new loop.

Figure 5 illustrates a loop in the investigative stage, where a new loop can start within the same stage or in a previous stage, depending on the judgment of the current situation. Figure 5 (Part 1) presents a detailed visualization of the integrated model's design process progression through combining UDA units in the investigative stage, with the corresponding reflection in action/on action and four classification parameters frameworks appended below each unit.

Figure 5 (Part 2) visualizes the three forms of cognitive transformations (a, b, c) in the design process progression represented in Figure 5 (Part 1) using a simplified tree diagram, where *a* maintains the main branch direction, *b* generates a new branch with a slight deviation in direction, and *c* regenerates a parallel main branch as a new direction for investigation.

Sketching Activity in the Investigative Stage

The scenario analysis is conducted for the stages of investigation, exploration, explanation, and persuasion using a simulated design task: *a smartphone solution with camera capabilities comparable to Digital Single Lens Reflex camera (DSLRs)*, employing sketches.

During the investigative stage, some parameters like *smartphone brand and model*, *basic camera parameters*, and *camera selling points* are analyzed. Figure 5 (Part 3) illustrates how the UDA unit combinations progress the investigation activity using sketches with the other two core actions.

The simulated scenario analysis combines the *1_1_Loop_N* in Figure 5 (Part 3) with actual sketch examples. The steps for the scenario-based simulation analysis for the investigative stage are summarized in Table 6. Considering that *information action* and *representation action* are interlinked, continuously progressing the investigation activity, the sequential combination of *information action* and *representation action* can be seen as a set that repeatedly progresses UP. However, due to the difficulty of representing this iterative cross-process quantitatively, it is simplified into iterative loops of combinations like *A and B*, *C and D*, and *E and F*. Although Table 6 does not detail this repetitive process, the expression in the *UP-Progression* column indicates the iteration of *information action* and *representation action* within a limited scope.

Table 6: *Simulated scenario analysis steps and detailed description in the investigative stage (consistent with "1_1_Loop_N").*

No.	Core actions & Cognition	Uncertainty Perception (UP) progression	Detailed description
A	Information action	*1UP1→1UP2* ⇅ *1UP2→1UP3*	Investigate the camera module parameters, target users, etc. of the flagship models of the major mobile phone brands (Apple, Samsung, Sony, Xiaomi, Oppo, Vivo, Huawei), so as to clarify the current status of the market and design.
B	Representation (sketching)		The investigation results in A are summarised in text through a sketch of level_1. To fulfil the investigative tasks set for A, A and B need to be crossed and repeated.
C	Information action	*1UP3→1UP4* ⇅ *1UP4→1UP5*	To enhance the product power of the design object, besides the basic parameters, it is also necessary to investigate the [appearance] and [special features] of competing products. The main investigation focuses on technical specifications, exterior design, AI-assisted features, and unique selling points.
D	Representation (sketching)		As with B, the data investigated and judged proper in C is visualized through sketches at Levels 1, 2, 3. This process is just as iterative as C and D cross-over.
E	Information action	*1UP5→1UP6* ⇅ *1UP6→1UP7*	Investigate the purchase costs, suppliers, self-development costs, markets, current technology trends, etc., to realize the products of each of the above-mentioned brands.
F	Knowledge sharing action		Working with E requires sharing, consulting, and discussing the investigated data with others in a timely manner so as to determine a more appropriate direction for the investigation, as well as working together to determine whether the investigated data is appropriate or erroneous. This is also a cross iterative process between E and F.
…	3 core actions & cognition	…	In the same loop, the above cycle of investigation and presentation similar to [AB] [CD] [EF] is continuously carried out, and the direction of the investigation is continuously clarified and more appropriate data are obtained through lateral (a) and vertical (b) transformations.
Z	Representation (sketching)	*1UPn-1→1UPn*	There are two possibilities for the UDA unit as the final UDA unit of this loop. One is the judgment that the current investigation has reached temporary saturation and can be progressed to a later stage. The other is that the activities of core action (e.g. sketching) and cognition conclude that the direction of the current investigation requires a significant shift, and therefore needs to be restarted into a new loop at the same stage.

Figure 6 (Part 1) visualizes the data collected from the interwoven process of *information action* and *sketching* in A and B in Figure 7 and Table 6, presented in both tabular and textual formats, categorized as sketch complexity level 1. These steps reflect an iterative intersection of continuous investigation of flagship smartphones representative of the current market and externalization with sketches as text and tables.

Subsequently, Figure 6 (Part 2) presents a visual record and summary of the further detailed investigation of the selected subjects using level 1, 2, and 3 sketches stated in C and D in Figure 7 and Table 6, conducted after an initial market survey. Due to copyright concerns, only the detailed investigation results of key parameters related to the design content, recorded in a level 1 sketch, are displayed.

Sketching Activity in the Exploratory Stage

During the explorative stage, the latest UPs obtained from the investigative stage loops (defining the design object) are utilized for exploratory design, focusing solely on sketching as a form of representation action here. The exploration delves into three aspects of the design object: *Camera Module Design*, *Basic and Unique Features*, and *Overall Design Details*. The upper part of Figure 7 illustrates how sketches detail the progression of design exploration by combining the UDA units. Table 7 summarizes the specific steps of the scenario-based simulation analysis for the explorative stage.

Table 7: *Simulated scenario analysis steps and detailed description in the exploratory stage (consistent with "2_1_Loop_N" in Figure 7).*

No.	Core actions & Cognition	Uncertainty Perception (UP) progression	Detailed description
A	Representation (sketching)	*1UP1→1UP2*	Based on the definition of the [Design Object] obtained during the investigation phase (which can be considered as UP), use sketches to exploratively visualize the [Imaging Module] of the smartphone (around the number of cameras, layout, focal lengths, lens parameters, sensors, etc.)
B	Representation (sketching)	*1UP2→1UP3*	In order to approach the effect of multifocal image quality of interchangeable lens cameras, as well as to realize the stabilized video function of physical gimbal-assisted shooting. Explore the design of a smartphone with a fixed-focal-length lens of 4 focal lengths and a micro gimbal, considering ergonomics and portability.
C	Representation (sketching)	*1UP3→1UP4*	In B, after the basic technical parameters and the styling framework have been defined, further exploration of the details of the smartphone's styling is required, as well as the selection of the supplier (performance vs. price) of the hardware for the selected parameters.
D	Information action	*1UP4→1UP5*	In C, it was found that the specifications of the selected hardware needed to be further verified as to whether they met the predefined criteria, and whether they were compatible with the design details. Therefore, it is necessary to collect, organize and analyze the information.
E	Representation (sketching)	*1UP5→1UP6*	Based on the data summarized in D, further visual exploration of more desirable smartphone styling and technical parameters is carried out.
F	Knowledge sharing action	*1UP6→1UP7*	Talk to them about the sketches obtained after the exploratory process in E, share design insights, and even brainstorm and gather feedbacks for each part of the sketch.
…	3 core actions & cognition	…	…
Z	Representation (sketching)	*1UPn-1→1UPn*	There are two possibilities for the UDA unit that is the last of this loop. One is the judgment that the exploration content in the moment has a certain degree of completion and can be progressed to a more later stage. The other is that the combined activities of core action (e.g., sketching) and cognition conclude that the current direction of exploration needs to make a significant transformation, and therefore needs to be restarted into a new loop at the same stage.

	Brand	Model	Camera		Unique selling points	Definition
1	Apple	iPhone 14 Pro	Triple	• 48MP Main: 24 mm, ƒ/1.78 • 12MP Ultra Wide: 13 mm, ƒ/2.2 • 12MP 3x Telephoto: 77 mm, ƒ/2.8	Photonic Engine	Enhances low-light performance and improves color accuracy, detail, and contrast
2	Sony	Xperia I III	Triple	• 12MP Main: 24mm, ƒ/1.7 • 12MP Ultra-wide: 16mm, ƒ/2.2 • 12MP Telephoto 70mm/105mm, ƒ/2.3, ƒ/2.8	Dual PD Sensor and Dual focal length telephoto lens	Enables fast and accurate autofocus and Offers versatile zoom capabilities
3	Xiaomi	Mi 13 Ultra	Quad	• 50MP Main: 23mm, ƒ/1.9 • 50MP Ultra-wide: 12mm, ƒ/2.0 • 50MP Telephoto 1: 75mm, ƒ/2.8 • 50MP Telephoto 2: 120mm, ƒ/3.2	1-inch sensor	Largest sensor size for improved low-light performance
4	Oppo	Find X6 Pro	Triple	• 50MP Main: 23mm, ƒ/1.8 • 50MP Ultra-wide: 15mm, ƒ/2.2 • 50MP Telephoto: 65mm, ƒ/2.6	MariSilicon X imaging NPU	Powerful AI processing for improved images
5	Vivo	X80 Pro	Quad	• 50MP Main: 23mm, ƒ/1.6 • 48MP Ultra-wide: 14mm, ƒ/2.2 • 12M Telephoto 1: 50mm, ƒ/1.9 • 8MP Periscope 125mm, ƒ/3.4	Zeiss T* coating	Reduces reflections and improves image quality
6	Huawei	P60 Pro	Triple	• 52MP Main: 23mm, ƒ/1.4~ƒ/4.0 • 50MP Ultra-wide: 13mm, ƒ/2.2 • 64MP Telephoto: 90mm, ƒ/3.5	XMAGE imaging technology	Advanced computational photography
7	Samsung	Galaxy S23 Ultra	Quad	• 200MP Main: 23mm, ƒ/1.7 • 12MP Ultra-wide: 13mm, ƒ/2.2 • 10MP Telephoto 1: 69mm, ƒ/2.4 • 10MP Telephoto 2: 230mm, ƒ/4.9	Adaptive Pixel technology	Combines pixels for better low-light shots
8	Huawei	Mate 60 Pro	Triple	• 50 MP Ultra: 24mm, ƒ/1.4~ƒ/4.0 • 20 MP Ultra-Wide: 13mm, ƒ/2.2 • 64 MP Periscope: 100mm, ƒ/3.5	Variable aperture	Adjusts aperture for depth of field control
9	Apple	iPhone 15 Pro	Triple	• 48MP Main: 24 mm, ƒ/1.6 • 12MP Ultra Wide: 13 mm, ƒ/2.2 • 12MP 3x Telephoto: 77 mm, ƒ/2.8	Periscope zoom lens	Longer optical zoom range

	Brand	CMOS	Lens Details & Manufacturer	AI Photography Solution	GPU Model & Manufacturer	Market & Technology Trends
1	Sony	• Main: Sony IMX557 • Ultra-wide: Sony IMX363 • Telephoto 1: Sony IMX663 • Telephoto 2: Sony IMX663	• ZEISS T* coating • ZEISS optics	AI super resolution zoom	Qualcomm Adreno 660	• Unique dual focal length telephoto lens • Slow-motion video capabilities • Adoption of AI-powered photography features • Integration of Alpha camera technologies
2	Xiaomi Mi 13 Ultra	• Main: Sony IMX989 • Ultra-wide: Sony IMX858 • Telephoto 1: Sony IMX858 • Telephoto 2: Sony IMX858	Leica optics	Xiaomi AI imaging algorithm	Qualcomm Adreno 740	• Larger sensor sizes • Advanced computational photography • Improved low-light performance
3	Oppo Find X6 Pro	• Main: Sony IMX989 • Ultra-wide: Sony IMX890 • Telephoto 1: Sony IMX890	Hasselblad optics	Oppo MariSilicon X NPU	Qualcomm Adreno 740	• Collaborations with camera brands • In-house imaging processors • Focus on fast charging and battery life
4	Vivo X80 Pro	• Main: Samsung GNV sensor • Ultra-wide: Sony IMX598 • Telephoto 1: Sony IMX663 • Telephoto 2: OmniVision OV08A10	• ZEISS T* coating • ZEISS optics	vivo V1+ imaging chip	Qualcomm Adreno 730	• Collaborations with lens manufacturers • Dedicated imaging processors • Emphasis on color science and portraits
5	Huawei P60 Pro	• Main: Sony IMX888 • Ultra-wide: Sony IMX858 • Telephoto 1: Sony IMX688	Huawei XMAGE lenses	Huawei XD Fusion Pro	Huawei Da Vinci NPU	• Advanced AI processing • Improved zoom capabilities • Adapting to sanctions and supply chain challenges
6	Samsung Galaxy S23 Ultra	• Main: Samsung ISOCELL HP2 • Ultra-wide: Sony IMX564 • Telephoto 1: Samsung ISOCELL S5KJN1 • Telephoto 2: Samsung ISOCELL S5KJN1	Samsung optics	Samsung Adaptive Pixel	Qualcomm Adreno 740	• High-resolution sensors • Improved night mode and astrophotography • Enhanced zoom and ultra-wide capabilities
7	Huawei Mate 60 Pro	• Main: Sony IMX988 • Ultra-wide: Sony IMX858 • Telephoto 1: Sony IMX989	Huawei XMAGE lenses	Huawei XD Fusion Pro	Huawei Da Vinci NPU	• Variable aperture technology • Emphasis on videography features • Continued focus on AI and computational photography
8	Apple iPhone 15 Pro	• Main: Sony sensor (TBA) • Ultra-wide: Sony sensor (TBA) • Telephoto 1: Sony sensor (TBA)	Apple-designed lenses	Apple Deep Fusion & Smart HDR	Apple GPU (5-core)	• Longer optical zoom ranges • Enhanced video capabilities • Focus on privacy and security

Figure 6: *Sketch samples depicting the design steps A, B, C, and D for Table 6 in the simulated design task; 1. Level 1 sketch samples obtained from the design investigation task, involving the intertwined iterative process of "information action" and "sketching" in A and B, as outlined in the simulated scenario of Table 6; 2. Level 1 sketch samples obtained from the design investigation task, involving the intertwined iterative process of "information action" and "sketching" in C and D, as outlined in the simulated scenario of Table 6.*

Figure 7 visualizes the steps from A to F through specific sketches, providing more understandable and convincing content for the scenario analysis sample of this stage. The investigative and exploratory stages involve loops of the set of *information* and *representation*. The distinction lies in the representation during the investigative stage being merely a summary and record of investigative data, whereas, in the exploratory stage, representation becomes a visual exploration based on investigative data, personal ideation, shared communication, etc.

Sketching Activity in the Explanatory Stage

During the explanatory stage, the latest UPs (i.e., visualized exploration solutions for the design object) obtained from the other stages, such as investigative or explorative loops, are presented to stakeholders. The aim is to gather diverse and beneficial feedback, providing a foundation for evaluating whether and how the current design solution should be iterated upon or further developed.

The explanatory stage primarily involves *knowledge sharing* actions, as spontaneous *information* and *representation* actions are unlikely during the explanation process, although not entirely impossible. The criterion for concluding a loop is not necessarily the occurrence of a significant shift (c: restart). In the explanatory stage, shift (c) refers to recognizing significant deficiencies in the explanation content based on feedback or accumulated UPs, necessitating a halt to the explanation process.

However, sometimes, even if a *restart* is deemed necessary, an immediate stop and iteration into another stage to start a new loop may be impossible due to predetermined timelines and processes. Therefore, the UPs accumulated from the explanatory stage loops (i.e., feedback collection) are integrated into the investigatory or exploratory stages after the explanatory activities are concluded. The specific simulated scenario analysis steps for using sketches as a visual medium, along with the corresponding sketches, are summarized in Figure 8.

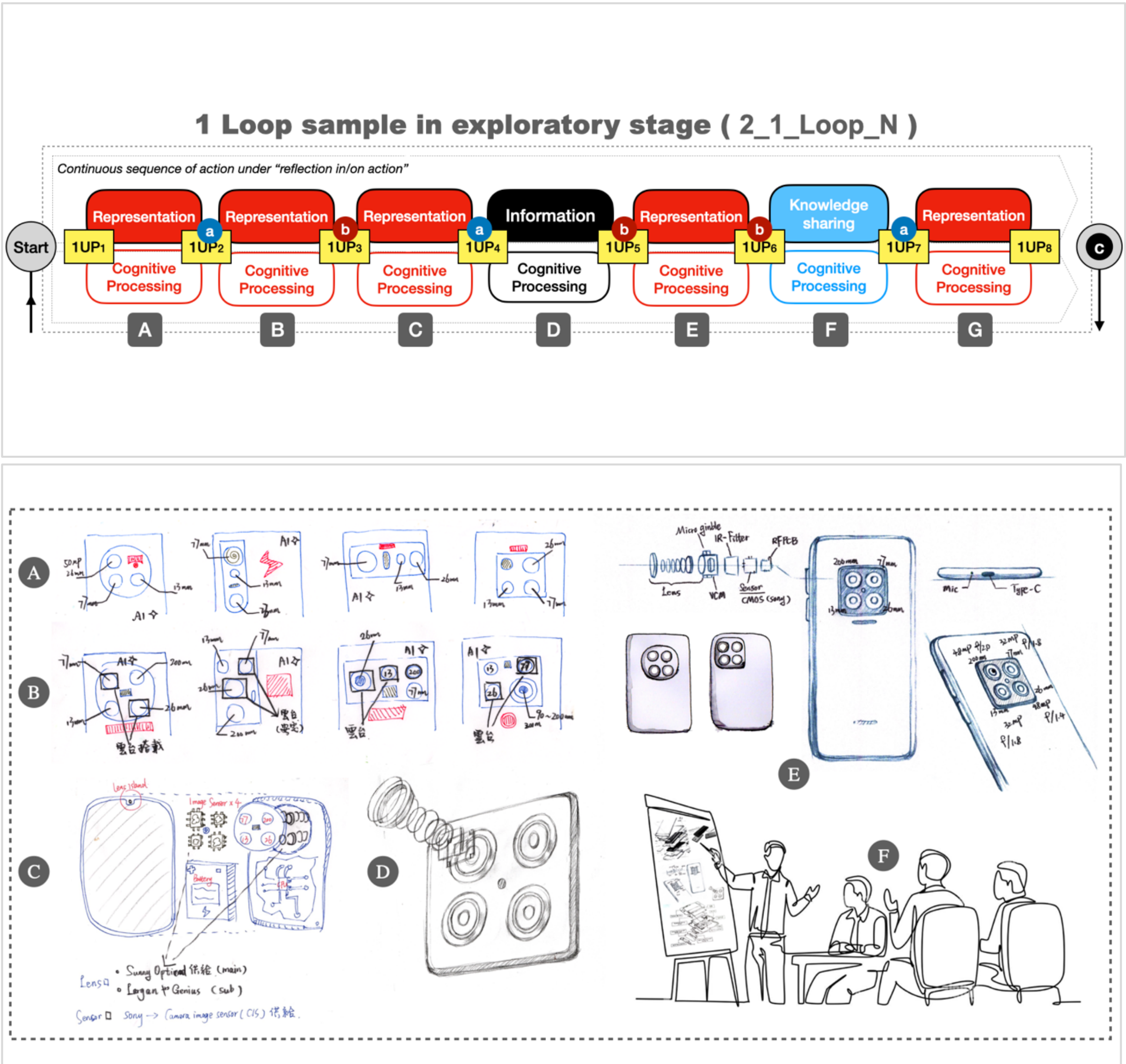

Figure 7: *One loop sample and corresponding sketches with levels 2, 3, and 4 in the exploratory stage (a: lateral transformation; b: vertical transformation; c: restart loop).*

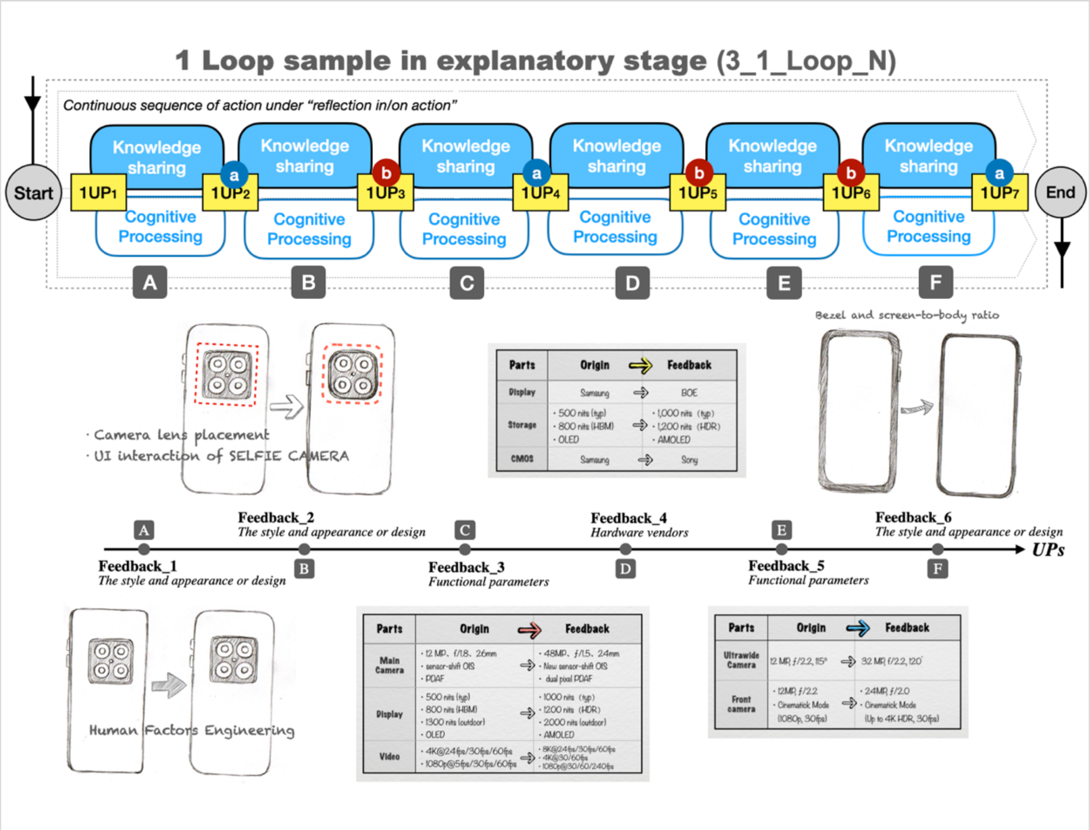

Figure 8: *One loop sample and corresponding sketches with levels 1, 2, and 3 in the explanatory stage.*

Sketching Activity in the Persuasive Stage

Before entering the persuasive stage, the design solution undergoes loops of investigation, exploration, and explanation (gathering feedback, considering market viability, etc.), resulting in a sketch judged suitable for prototyping and persuasion.

To bring the current design solution into practice and initiate production, the sketch is used to persuade a broader audience of stakeholders (investors or management). The overall progression mirrors the explanatory stage, with *knowledge sharing* being the sole action throughout the persuasive stage. Similar to the explanatory phase, once the persuasive process ends, the UPs accumulated during the persuasive loops are collectively reflected into the investigative, exploratory, or explanatory stages. Compared to the explanatory stage, sketches in the persuasive stage have higher fidelity, and the feedback received is likely more market-oriented. Although the feedback content may vary, the simulation steps for the UDA unit progression in the persuasive stage can be referenced in the upper part of Figure 8, while specific scenario analysis can follow the model presented in the lower part of Figure 8.

Discussion

This study proposed a comprehensive sketching activity model by integrating a generic sketch taxonomy with the UDA model, aiming to advance the theoretical understanding and support for sketching in the design process. The model's effectiveness has been explored in terms of its feasibility, integrity, and accuracy.

The feasibility of the proposed model has been investigated through a systematic review of existing sketch taxonomies (Section 3), which provided a basis for selecting and integrating relevant classification criteria, basically addressing the Q1.

The development of a generic sketch taxonomy (Section 5, 6.1) and its integration with the UDA model (Section 6.2) have further demonstrated the feasibility of the proposed approach, basically answering the Q4. However, the model's feasibility should be interpreted with caution, as it has been validated using a limited number of simulated scenarios (Section 7).

Regarding the model's integrity, the analysis using the reflection-in/on-action framework (Section 6.1) has provided initial evidence for the coherence and consistency of the model's components, including the UDA actions and the sketch taxonomy, contributing to the answer to the Q4. Nevertheless, further empirical studies are needed to confirm the model's integrity in diverse design contexts. The accuracy of the model in capturing the essential features of sketching activities has been examined through scenario-based validation (Section 7), which has shown that the selected parameters, such as cognitive approach, intention, function, and complexity, can effectively describe various sketching actions in the design process, preliminarily answering Q2. The UDA model has been identified as a potentially suitable theoretical unit for describing sketching activities, which to some extent answers Q3, and the integrated model has demonstrated some explanatory power in capturing the key characteristics of sketching activities across different design stages, contributing to the answer Q5. However, the model's accuracy should be further validated through more extensive empirical studies.

Conclusion

The proposed comprehensive sketching activity model integrates a validated sketch taxonomy with the UDA model, advancing the theoretical understanding and support for sketching in the design process. The main contributions include:

1. Providing an effective method for analyzing sketching activities, considering representation, cognition, and reflection, thus facilitating the analysis of relationships between sketching behaviors and other core design actions.

2. Bridging the gaps between static sketch taxonomies and dynamic design process models, as well as the long-standing lack of generic taxonomies and models describing discrete sketching activities in the design process.

3. Offering a preliminarily validated comprehensive framework to guide further research on design sketch support and alleviating intelligence deficiencies in sketch inhibition.

The value of the proposed model lies in its potential to enhance the learning, practice, and tool development for design sketching by providing a systematic understanding of sketching behaviors within the broader context of design activities. This study contributes to the efforts in mitigating sketch inhibition among student designers and promoting the effective use of sketching in design.

Future research directions are as follows (as the answers to Q6):

1. Conducting more empirical studies to validate the model's generalizability.

2. Exploring the social and collaborative aspects of sketching.

3. Investigating the model's adaptability to different design disciplines.

4. Integrating the model with other design methods and tools.

5. Applying the model to develop sketch-based design support systems and educational interventions.

As design challenges become increasingly complex and technology advances rapidly, a deeper understanding of the cognitive and behavioral aspects of sketching is crucial. The proposed comprehensive sketching activity model has the potential to alleviate sketch inhibition, particularly in terms of intellectual issues, by providing a structured framework for understanding the role and use of sketches in the design process.

By integrating a generic sketch taxonomy with the UDA model, the proposed model offers a guiding theoretical framework that can support learning and enhance designers' understanding of the importance and effective application of sketches. This improved understanding may contribute to reducing the reluctance to sketch and promoting more effective sketching behaviors in design practice.

In the future, the integrated model could serve as a significant theoretical basis in higher education and professional settings to enhance the understanding of sketches' roles in the design process. Research on developing design support tools tailored for design education or promoting design thinking, including tools to manage and alleviate SI symptoms, shows promising potential.

References

Alcaide-Marzal, J., Diego-Más, J. A., Asensio-Cuesta, S., & Piqueras-Fiszman, B. (2013). *An exploratory study on the use of digital sculpting in conceptual product design*. Design Studies, 34 (2), p. 264–84. https://doi.org/10.1016/j.destud.2012.09.001

Altenburger, E., Falche, I., & Gwin, H. (2022). *Relaxing design students sketch inhibition: Experiences with theoretical grounding and impermanent media*. International Journal of Art and Design Education, 42(1), p. 69–85. https://doi.org/10.1111/jade.12446

Amer, M., Daim, T. U., & Jetter, A. (2013). *A review of scenario planning*. Futures, 46, p. 23–40. https://doi.org/10.1016/j.futures.2012.10.003

Bánáthy, B. H. (1996). *Designing social systems in a changing world*. Contemporary Systems Thinking. https://doi.org/10.1007/978-1-4757-9981-1

Bedny, G. Z., & Karwowski, W. (2004). *Activity theory as a basis for the study of work*. Ergonomics, 47(2), p. 134–53. https://doi.org/10.1080/00140130310001617921

Bilda, Z., & Demirkan, H. (2003). *An insight on designers sketching activities in traditional versus digital media*. Design Studies, 24(1), p. 27–50. https://doi.org/10.1016/s0142-694x(02)00032-7

Booth, J. W., Elkin, A. Ramani, T. K., & Reid, T. (2016). *Interventions for teaching sketching skills and reducing inhibition for novice engineering designers*. Design Studies, 43, p. 1–23. https://doi.org/10.1016/j.destud.2015.11.002

Buxton, B. (2007). *Sketching user experiences: getting the design right and the right design*. https://cds.cern.ch/record/1190758/files/9780123740373_TOC.pdf

Cash, P., & Maier, A. (2016). *Prototyping with your hands: the many roles of gesture in the communication of design concepts*. Journal of Engineering Design, 27(1–3), p. 118–45. https://doi.org/10.1080/09544828.2015.1126702

Cash, P., & Kreye, M. E. (2017). *Uncertainty driven action (UDA) model: a foundation for unifying perspectives on design activity*. Design Science, 3. https://doi.org/10.1017/dsj.2017.28

Cash, P., & Kreye, M. (2018). *Exploring uncertainty perception as a driver of design activity*. Design Studies, 54, p. 50–79. https://doi.org/10.1016/j.destud.2017.10.004

Ching, F. D. K. (2003). *Architectural graphics*. New York, John Wiley, and sons, inc.

Christensen, B. T., & Ball, L. J. (2016). *Fluctuating epistemic uncertainty in a design team as a metacognitive driver for creative cognitive processes*. CoDesign, 14(2), p. 133–52. https://doi.org/10.1080/15710882.2017.1402060

Clune, S., & Lockrey, S. (2014). *Developing environmental sustainability strategies, the double diamond method of LCA and design thinking: A case study from aged care*. Journal of Cleaner Production, 85, p. 67–82. https://doi.org/10.1016/j.jclepro.2014.02.003

Court, A. (1997). *The relationship between information and personal knowledge in new product development*. International Journal of Information Management, 17(2), p. 123–38. https://doi.org/10.1016/s0268-4012(96)00054-0

Crismond, D., & Adams, R. (2012). *The informed design teaching and learning matrix*. Journal of Engineering Education, 101(4), p. 738–97. https://doi.org/10.1002/j.2168-9830.2012.tb01127.x

Cross, N. (2000). *Engineering design methods: Strategies for product design (3th Ed.)*. Wiley. http://elibrary.unpas.ac.id/index.php?p=show_detail&id=17843

David, F. R., & Tat, Y. T. (1990). *Models of visual thinking by novice designers*. Design Engineering, 27, p. 145–152. Chicago, Illinois, United States of America: ASME 1990 Design Technical Conferences. https://doi.org/10.1115/detc1990-0120

De Menezes, A. M. (2005). *Sketching and visual perception in conceptual design: Case studies of novice and expert architecture students*. PhD thesis, University of Sheffield.

Dinar, M., Shah, J., Cagan, J., Leifer, L., Linsey, J., Smith, S. M., & Hernandez, N. V. (2015). *Empirical studies of designer thinking: past, present, and future*. Journal of Mechanical Design, 137(2). https://doi.org/10.1115/1.4029025

Eckert, C., Blackwell, A. F., Stacey, M., Earl, C., & Church, L. (2012). *Sketching across design domains: Roles and formalities*. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 26(3), p. 245–66. https://doi.org/10.1017/s0890060412000133

Eris, O., Martelaro, N., & Badke-Schaub, P. (2014). *A comparative analysis of multimodal communication during design sketching in co-located and distributed environments*. Design Studies, 35(6), p. 559–92. https://doi.org/10.1016/j.destud.2014.04.002

Evans, J. (2008). *Dual-Processing accounts of reasoning, judgment, and social cognition*. Annual Review of Psychology, 59(1), p. 255–78. https://doi.org/10.1146/annurev.psych.59.103006.093629

Ferguson, E. S. (1994). *Engineering and the Mind's Eye*. MIT Press.

Fraser, I., & Henmi, R. (1993). *Envisioning architecture: An analysis of drawing*. http://ci.nii.ac.jp/ncid/BA24017657

Gero, J. S., & Kannengiesser, U. (2004). *The situated function–behavior–structure framework*. Design Studies, 25(4), p. 373–91. https://doi.org/10.1016/j.destud.2003.10.010.

Goel, V. (1995). *Sketches of thought*. London: MIT Press.

Goldschmidt, G. (1991). *The dialectics of sketching*. Creativity Research Journal, 4(2), p. 123–143. https://doi.org/10.1080/10400419109534381

Goodspeed, R., Riseng, C. M., Wehrly, K. E., Yin, W., Mason, L. A., & Schoenfeldt, B. (2016). *Applying design thinking methods to ecosystem management tools: Creating the Great Lakes Aquatic Habitat Explorer*. Marine Policy, 69, p. 134–45. https://doi.org/10.1016/j.marpol.2016.04.017

Hatchuel, A., Masson, P., & Weil, B. (2004). *C-K theory in practice: lessons from industrial applications*. Proceedings of design 2004, the 8th International Design Conference, Dubrovnik, Croatia, p. 245–58. http://m.designsociety.org/download-publication/19760/c-k_theory_in_practice_lessons_from_industrial_applications

Hua, M., Han, J., Wang, P., & Huang, S. (2018). *Towards a comprehensive understanding of design sketch – a literature review of design sketch taxonomy and considerations for future research*. Ideology, 3(3), p. 261-277.

Ian, D. V. (2016). Back to basics: using esquisses to develop core design skills. Proceedings of the 18th International Conference on Engineering and Product Design Education (E&PDE16), Design Education: Collaboration and Cross-Disciplinarity, Aalborg, p. 083–088.

Johnson, G., Gross, M. D., Hong, J. I., & Yi-Luen, E. (2007). *Computational support for sketching in design: A review*. Foundations and Trends in Human-Computer Interaction, 2(1), p. 1–93. https://doi.org/10.1561/1100000013

Kiernan, L., & Ledwith, A. (2014). *Is design education preparing product designers for the real world? A study of product design graduates in Ireland*. Design Journal, 17(2), p. 218–37. https://doi.org/10.2752/175630614x13915240576022

Kranakis, E., & Ferguson, E. S. (1994). *Engineering and the mind's eye.* Technology and Culture, 35(2), 402. https://doi.org/10.2307/3106309

Leblanc, T. (2015). *Sketching as a thinking process*. Proceedings of the 17th International Conference on Engineering and Product Design Education (E&PDE15), Great Expectations: Design Teaching, Research & Enterprise, Loughborough, UK, 606–11. https://education.designsociety.org/download-publication/38510/SKETCHING+AS+A+THINKING+PROCESS

Lugt, V. R. (2005). *How sketching can affect the idea generation process in design group meetings*. Design Studies, 26(2), p. 101–22. https://doi.org/10.1016/j.destud.2004.08.003

McGown, A., Green, G., & Rodgers, P. (1998). *Visible ideas: Information patterns of conceptual sketch activity*. Design Studies, 19(4), p. 431–53. https://doi.org/10.1016/s0142-694x(98)00013-1

Olofsson, E., & Sjolen, K. (2005). *Design sketching*. KEEOS Design Books AB, Sweden.

Pei, E., Campbell, I., & Evans, M. A. (2011). *A taxonomic classification of visual design representations used by industrial designers and engineering designers*. Design Journal, 14(1), p. 64–91. https://doi.org/10.2752/175630610x12877385838803

Pei, E. (2010). *Building a common language of design representations for industrial designers and engineering designers*. https://dora.dmu.ac.uk/xmlui/handle/2086/6140?show=full

Plattner, H., Meinel, C., & Leifer, L. (2010). *Design Thinking: Understand - Improve - Apply*. Berlin: Springer.

Plimmer, B., & Apperley, M. (2005). *From sketch to Blueprint: Supporting the creative design process*. Proceedings of Workshop on Improving and Assessing Pen-Based Input Techniques. https://www.researchgate.net/publication/228817965_From_Sketch_to_Blueprint_Supporting_the_creative_design_process

Purgathofer, P., & Baumann, K. (2010). *Sketching user experience: Getting the design right and the right design*. Information Design Journal, 18(1), p. 88–89. https://doi.org/10.1075/idj.18.1.13pur

Reymen, I. M. M. J. (2001). *Improving design processes through structured reflection: A domain-independent approach*. Ph.D. Thesis, Technische Universiteit Eindhoven. http://papers.cumincad.org/data/works/att/4dd3.content.pdf

Rowe, P. G. (1987). *Design Thinking*. MIT Press. https://www.amazon.com/Design-Thinking-Press-Peter-Rowe/dp/026268067X

Schembri, M., Farrugia, P., Wodehouse, A. J., Grierson, H., & Kovacevic, A. (2015). *Influence of sketch types on distributed design team work*. CoDesign, 11(2), p. 99–118. https://doi.org/10.1080/15710882.2015.1054841

Schön, D. A. (1992). *Designing as reflective conversation with the materials of a design situation*. Knowledge-Based Systems, 5(1), p. 3–14. https://doi.org/10.1016/0950-7051(92)90020-g

Schön, D. A., & Wiggins, G. (1992). *Kinds of seeing and their functions in designing*. Design Studies, 13(2), p. 135–56. https://doi.org/10.1016/0142-694x(92)90268-f

Schön, D. A., & DeSanctis, V. (1986). *The reflective practitioner: How professionals think in action*. The Journal of Continuing Higher Education, 34(3), p. 29–30. https://doi.org/10.1080/07377366.1986.10401080

Scrivener, S. A. R, Ball, L. J., & Tseng, W. (2000). *Uncertainty and sketching behaviour*. Design Studies, 21(5), p. 465–481. https://doi.org/10.1016/s0142-694x(00)00019-3

Shammout, M. W., Shatanawi, M., & Naber, S. (2013). *Participatory optimization scenario for water resources management: A case from Jordan*. Water Resources Management, 27(7), p. 1949–62. https://doi.org/10.1007/s11269-013-0264-9

Simon, H. A. (1996). *The sciences of the artificial (3rd Ed.)*. https://dl.acm.org/citation.cfm?id=237774

Stumpf, S., & McDonnell, J. (2002). *Talking about team framing: Using argumentation to analyze and support experiential learning in early design episodes*. Design Studies, 23(1), p. 5–23. https://doi.org/10.1016/s0142-694x(01)00020-5

Suwa, M., Gero, J., & Purcell, T. (2000). *Unexpected discoveries and s-invention of design requirements: Important vehicles for a design process.* Design Studies, 21(6), p. 539–67. https://doi.org/10.1016/s0142-694x(99)00034-4

Thurlow, L., Ford, B. J., & Hudson, G. (2018). *Skirting the sketch: An analysis of sketch inhibition within contemporary design higher education*. International Journal of Art and Design Education, 38(2), p. 478–91. https://doi.org/10.1111/jade.12207

Thurlow, L. (2019). *Designers who don't draw: An investigation into sketch inhibition among undergraduate designers*. https://dora.dmu.ac.uk/bitstream/2086/18656/1/Lisa%20Thurlow%20-%20e-thesis.pdf

Tovey, M. (1989). *Drawing and CAD in industrial design*. Design Studies, 10(1), p. 24–39. https://doi.org/10.1016/0142-694x(89)90022-7

Valkenburg, R., & Dorst, K. (1998). *The reflective practice of design teams*. Design Studies, 19(3), p. 249–271. https://doi.org/10.1016/s0142-694x(98)00011-8

Verstijnen, I. M, Leeuwen, C. V., Goldschmidt, G., Hamel, R., & Hennessey, J. (1998). *Sketching and creative discovery*. Design Studies, 19(4), p. 519–46. https://doi.org/10.1016/s0142-694x(98)00017-9

Visser, W. (2006). *Designing as construction of representations: A dynamic viewpoint in cognitive design research*. Human-Computer Interaction, 21(1), p. 103–52. https://doi.org/10.1207/s15327051hci2101_4

Vistisen, P. (2015). *The roles of sketching in design: Mapping the tension between functions in design sketches*. Nordic Design Research Conference. https://doi.org/10.21606/nordes.2015.003

Wilson, T. D. (1999). *Models in information behaviour research*. Journal of Documentation, 55(3), p. 249–70. https://doi.org/10.1108/eum0000000007145

Yang, M. C. (2008). *Observations on concept generation and sketching in engineering design*. Research in Engineering Design, 20(1), p. 1–11. https://doi.org/10.1007/s00163-008-0055-0

Yang, M. C., & Cham, J. (2006). *An analysis of sketching skill and its role in early stage engineering design*. Journal of Mechanical Design, 129(5), p. 476–82. https://doi.org/10.1115/1.2712214

Yang, M., You, M., & Chen, F. (2005). *Competencies and qualifications for industrial design jobs: Implications for design practice, education, and student career guidance*. Design Studies, 26, p. 15–189. https://doi.org/10.1016/j.destud.2004.09.003

Zorriassatine, F., Wykes, C., Parkin, R., & Gindy, N. (2003). *A survey of virtual prototyping techniques for mechanical product development.* Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture, 217(4), p. 513–530. https://doi.org/10.1243/095440503321628189