# Developing technology students' hierarchical thinking during iterative processes of designing through sketching activities

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## ABSTRACT

The development of students' hierarchical thinking during iterative processes of designing through sketching activities is a crucial part of design education as it supports the connection between students' design intentions and its material embodiment. To this end, this paper discusses how different types of sketching activities can facilitate the development of hierarchical thinking in design activities. In this paper, we define hierarchical thinking as the ability to move between abstract and concrete representations through varying levels of specificity as well as the journey from global to specific representations. Doing this, we explore how using different sketching activities can allow students to explore a range of design intentions and physical embodiments at different levels of abstraction and detail. The paper also discusses how the idea of hierarchical thinking can support design educators to teach students to engage with their design processes more productively on a need-to-know basis. By teaching students to move between different levels of abstraction and detail effectively, teachers can support students to develop a more nuanced and comprehensive understanding of their designerly processes. Overall, this paper highlights the importance of modelling through sketching and hierarchical thinking in design education and practice.

*Key Words: Hierarchical Thinking, Design Representations, Iterative Processes of Designing*

## 1. INTRODUCTION

One of the main aims of design and technology education is to foster pupils' ability to engage in complex, real-world designing. To do this, pupils engage in authentic, collaborative design-based learning projects in which they are challenged to identify and address design challenges. However, these design challenges are often presented in a prescriptive manner, following a linear sequence of design activities, that often deny pupils the opportunity to explore complexity by connecting given problem scenarios, and solutions in a fit-for-purpose and intentional manner (Haupt, 2018). In addition, novice designers might lack the experience of connecting design 'problems' with suitable or fit-for-purpose design solutions. Practical encounters of what happens in technology classrooms reveal that pupils often engage in fragmented and disjointed activities

where their sketches or 3D models have limited conceptual connection with the bigger socio-technological issues articulated in the scenarios they are supposed to address (Haupt, 2018). Further to this, instruction on using design representations to support designing is often neglected at the expense of teaching students to document design processes. We believe that the obstacles posed by these challenges make it difficult for design and technology educators to guide students in linking their design goals with the tangible realization of their concepts.

Currently, research on teaching how to foster design capability in a manner that allows pupils to develop coherence between material solutions, design problems and design intentions, seem limited (Haupt, 2018). This limitation consequently results in fostering misconceptions regarding the intentional and integrated nature of designing. As such, there is a need to develop tools that can support the ways in which designers engage in designing, while maintaining coherence of scenario, intentions, challenges, and solutions. To this end, this paper presents a teaching tool through which designers' hierarchical thinking can be fostered. To create this framework, we draw upon various design education ideas, including iterative processes of designing (Kimbell & Stables, 2008), hierarchical thinking (Haupt, 2018), and the creation of design representations (Pei & Self, 2022).

In this paper, we present a novel teaching tool for using sketching activities to develop design and technology students' hierarchical thinking. This framework explains how the intentional use of different types of sketches give rise to coherent and connected design ideas. This framework can support teachers of design education to enhance their understanding and practice related to the role of sketching during processes of designing. This framework is important for teachers of design, who can use students' external representations to provide feedback, scaffold future action and reflection activities, or guide students to available tools and materials to examine and realise their design ideas.

## 2. LITERATURE REVIEW

### *2.1. Hierarchical thinking during iterative designing*

During the iterative design process, hierarchical thinking plays a crucial role in supporting students' ability to maintain coherence of design intentions with related material embodiments. Historically, hierarchical thinking originated from Hierarchy Theory, which is concerned with how humans approach complex problems (Allen & Starr, 2017). This approach consists of viewing problems and their solutions in a set of interrelated levels. As such, hierarchical thinking indicates a relationship between the starting level of thinking and its following levels (Medland, 2007). When applied to design cognition, this implies that designers progress through processes of designing by engaging in various interrelated levels of thinking that could be distinguished from each other based on the content of designers' thoughts as well as the varying levels of specificity revealed in their external representations (Goel, 2014; Haupt, 2018; Kamffer, 2019).

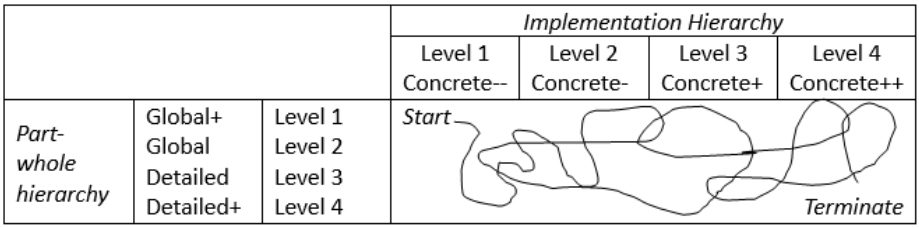
Over the past 20 years, various models have emerged in the literature explaining how professional designers engage in hierarchical thinking. For example, Gero's (1998) Function Behaviour Structure (FBS) framework; Vermaas's (2009) Model of Conceptual layering of technical devices

and Haupt's (2018) cognitive tool for guiding coherent decision making. These frameworks primarily focus on what designers think about during designing, including their design goals, requirements, functionality, behaviour and physicality of the artefact that they are designing. However, a notable omission from these hierarchical thinking descriptions is an examination of how design representations, such as sketching, support or constrain the movement between the different levels of specificity. While sketching is often celebrated as a medium to foster design thinking, its value and approach in educational settings remain contentious (Härkki et al., 2018; Sung et al., 2019). As such, there's a need to question to what extent design related sketching skills are taught explicitly in schools and if these methods should mirror professional practices.

Within some design and technology education curricula, there often appears to be an emphasis on honing technical proficiencies, such as technical drawing often at the expense of foundational design skills like sketching and model making (Delahunty et al., 2012). This prioritisation might unintentionally overshadow the importance of nurturing innate designing abilities and the intuitive exploration enabled by sketching. The emphasis on technical skills over essential design skills creates a skewed understanding of the design process (Delahunty et al., 2012). Sketching and model making, for instance, are fundamental to the iterative design process, fostering creativity, flexibility, and the ability to rapidly visualize and refine ideas (Kimbell & Stables, 2008). By not giving these foundational skills the attention they deserve, we risk cultivating a generation of designers proficient in execution but potentially limited in innovative thinking. This imbalance is concerning, as it could stifle the emergence of novel design solutions. To better shape and guide the design journey, especially from an educational standpoint, it's imperative to understand the intricate layers of design thinking.

To support teachers in facilitating students' thinking processes, we highlight two hierarchical movements that are present during students' processes of iterative designing, including part-whole hierarchical thinking and implementation hierarchical thinking. We draw on Visser's (2006) systematic Decomposition Approach, shown in Figure 1, to highlight the non-linear, yet hierarchical movement between different levels of design thinking. We contend that evidence of the hierarchical thinking can be explored in the external representations that designers generate during their processes of designing, which we will explore in Section 3 of the paper.

Figure 1: Visser's (2006) systematic decomposition approach




Part-whole hierarchical thinking refers to the way in which designers can decompose a design idea into smaller parts and to think about the relationship between the parts that make up the

whole design (Visser, 2006). In essence, part-whole hierarchical thinking entails a designers' ability to break a design down into constituent elements, sub-systems or components, which all contribute to the overall functioning of the whole design. Teaching students this thinking skill helps them to analyse and understand the design by examining the relationships and interactions between different components of the design. Furthermore, this skill helps designers to manage complexity by identifying components and understanding how changes in one part affect the whole design.

Implementation hierarchical thinking refers to the way in which designers represent their ideas in various levels of abstraction in terms of its implementation and realisation (Visser, 2006). These representations help the designers to consider the different levels of implementation, from the overall form to specific materials, technologies, aesthetics, and interfaces. Essentially, implementation hierarchical thinking helps designers to understand various design realisation factors, such as how design ideas can be developed from the conceptual phase into a tangible product, assessing the feasibility and cost implications of different implementation choices and to determine the manufacturing processes, materials, and technologies required for implementation.

Hierarchical thinking is essential for students to design effective solutions to real-world problems as it helps them to effectively analyse, organise and represent the complex relationships and dependencies resulting from their design ideas. This is especially important where the complexity of design problems and their solutions can be overwhelming. In this paper, we argue that students' ability to think in hierarchical ways, depends critically on the nature and types of design representations that students create during designing. These representations might include verbal, visual or gestural representations. For this paper, we focus solely on sketching and drawings as a vehicle for demonstrating and developing hierarchical thinking. Future research will include other representational media, including physical modelling and prototyping.

### *2.2. Design sketching as a cognitive activity*

Sketching is a fundamental tool that has been traditionally used by designers to support design thinking and communication. While the process of thinking and decision making through the design process increasingly involves the use of modern digital technologies (such as CAD) and advanced physical prototyping methods (Karabiyik et al., 2023), the role of sketching as a tool to support design thinking remains highly valued. In the context of design education, design sketching is a journey that designers undertake where they create and use external representations / visual displays on a 2D surface (such as paper or a digital tablet) to support the exploration, manipulation, visualisation and evaluation of a product's spatial configurations (Goldschmidt, 1991; Yi-Luen Do, 2005). Such explorations support the development of their hierarchical thinking (Haupt, 2018; Visser, 2006) in exploring the various components in their design ideas, and also the various levels of abstractions needed to realise the design idea.

While many people view rendered and highly aesthetic perspective sketches that communicate a conceptual design (or product) as the gold standard of sketching, the journey in getting to that rendered final concept is often under-valued and sometimes even dismissed. Design sketching is an iterative and hierarchical process where arguments in the mind's eye oscillate and are

externalised and developed on paper. It is imperative that these dialectics of sketching (Goldschmidt, 1991) are understood and embraced in D&T classrooms where sketching can become a powerful sense making tool to support idea generation, self-reflection, self-expression and reflexive thought (Jonson, 2002; van der Lugt, 2005).

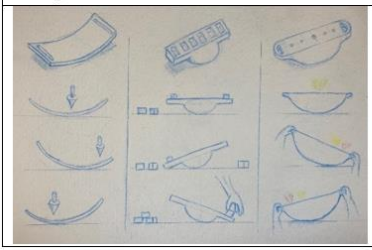
At a fundamental level, sketching can be considered as the externalisation of thinking processes during a design task, however, the value of the process goes beyond the marks created on paper by the user. Sketching presents the student with the opportunity to explore and reflect on complex, tacit and explicit internal processes (Dix & Gongora, 2011). The production of marks on paper not only records the design journey process but it also serves as a mental buffer enabling the student to retrieve, manipulate and synthesise information in an efficient fashion. This extends beyond the final sketches and helps the student to free up their mind to engage and think efficiently about the design task at hand.

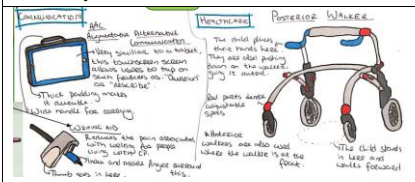
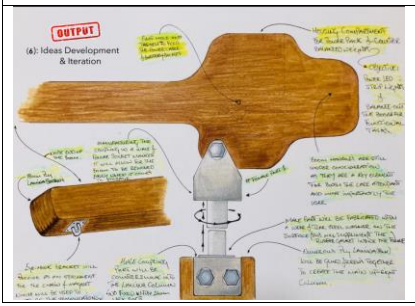
While it is widely accepted that sketching plays a key role in supporting design thinking, it is important that educators understand the cognitive role that external representations such as sketches play during designing. It is our belief that teachers could enhance their support for students during designing when they understand the cognitive role that sketches play in externalising and organising thoughts about design ideas, as well as, understanding the way in which sketches facilitate reflection, exploration, communication, and offloading information for the purposes of problem solving, ideation, comprehension and appraisal.

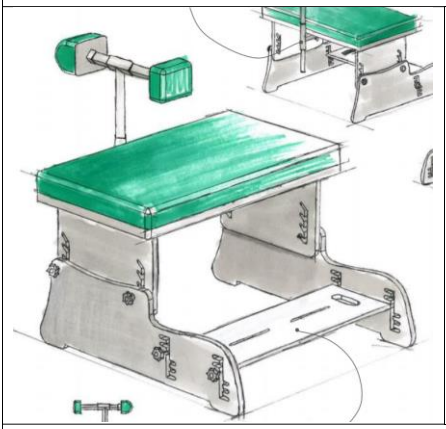
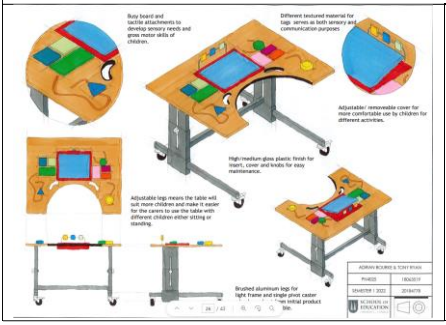
## 3. A TEACHING TOOL TO SUPPORT STUDENTS' HIERARCHICAL THINKING DURING DESIGNING

In developing a tool for design and technology educators to support the hierarchical thinking embedded in students' design sketches, we draw on the work of Pei & Self (2022), who developed a taxonomy of design representations in the context of professional design education. The work of Pei and Self (2022) provides a comprehensive and well-structured taxonomy that differentiates between different design representations and aided us in the analysis and interpretation of hierarchical elements in design representations. For this conference paper, we draw on eight different sketches that might be applicable to design and technology education and illustrate how they reflect various levels of hierarchical thinking. In the following teaching tool, we demonstrate that the properties in the different types of sketches could provide more information about the hierarchical thinking of students.

Figure 2: Teaching tool to support hierarchical thinking during sketching activities.

| Sketch types | Properties | Part-whole hierarchy | Implement ation hierarchy | Iterative design phase |
|---|---|---|---|---|
| **Idea sketches** | | | | |
|  | - Quick externalisation of ideas<br>- Simple line work<br>- Focus on design idea | Focuses on Global idea Level 1<br><br>(Global +) | Abstract ideas, with little references to implementat ion intentions<br><br>(Concrete --) | During the initial phases of an idea |
| **Study sketches** | | | | |
|  | - Exploratory sketches to investigate appearance, proportion, scale, layout, configuration, or mechanism.<br>- Loose use of tone and colour | Focusses on Global idea Levels 1 and 2<br><br>(Global) | Abstract ideas, with little references to implementat ion intentions<br><br>(Concrete --) | During the initial phases of an idea |

| | | | | |
|---|---|---|---|---|
| **Referential sketches** | | | | |
|  | - Used to record observations of stimuli for future reference, inspiration or as a metaphor<br>- Emphasis on visual character | Focusses on Global idea Levels 1 and 2<br><br>(Global) | Abstract ideas, with little references to implementation intentions<br><br>(Concrete --) | During the initial phases of an idea |
| **Memory sketches** | | | | |
|  | - Expanding thoughts about the initial idea.<br>- Elaboration in the form of mind-maps, annotations, notes.<br>- Tends to be information related to the scenario of use | Focusses on Global idea Levels 1 and 2<br><br>(Global) | Abstract ideas, with little references to implementation intentions<br><br>(Concrete --) | During the initial phases of an idea |
| **Coded sketches** | | | | |
|  | - Informal categorisation of design information.<br>- Tend to focus on operating and working principles of systems and components. | Focusses on detail idea Levels 2 and 3<br><br>(Detailed) | Developing ideas, with references to the physical and functional nature of the design ideas<br>(Concrete -) | During the middle phases of an idea realisation |
| **Information sketches** | | | | |
|  | - Quick communication of design features.<br>- Uses annotation and some colour.<br>- Tends to focus on design intentions and construction information. | Focusses on detail idea Levels 2 and 3<br><br>(Detailed) | Developing ideas, with references to the physical and functional nature of the design ideas<br>(Concrete -) | During the middle phases of an idea realisation |

| | | | | |
|---|---|---|---|---|
| **Rendered sketches** | | | | |
|  | - Focuses on representing a clearly defined idea proposal<br>- Use of colour and tone to enhance detail and realism<br>- Focuses on overall form and aesthetics | Focusses on detail idea Levels 2 and 3<br><br>(Detailed) | Developing ideas, with references to the physical nature of the design ideas (Concrete +) | During the middle phases of an idea realisation |
| **Prescriptive sketches** | | | | |
|  | - Focuses on representing accurate technical details.<br>- Details include information about mechanisms, materials, manufacturing, dimensions<br>- Focuses on parts within a system | Focusses on detail idea Levels 3 and 4<br><br>(Detailed +) | Developing ideas, with references to the functional and implementation intentions of the design ideas (Concrete ++) | During the middle to end phases of an idea realisation |

Rooted in the framework of Pei and Self (2022), Visser (2006) and Kimbell and Stables (2008), this teaching tool serves primarily design and technology teachers aiming to cultivate and enhance hierarchical thinking through design sketches within their students. The taxonomy of design representations by Pei and Self (2022), adeptly suited for professional design education, also finds relevance in the context of school-level design education, making it a versatile tool.

Using the tool is envisioned as an iterative process. As students progress through design projects, teachers can refer to the tool during specific sketching activities. The eight distinct sketches, carefully selected from the broader taxonomy for their relevance to design and technology education, act as markers or checkpoints. Each sketch type reflects a unique level of hierarchical thinking, allowing teachers to pinpoint and understand the depth and direction of a student's design cognition at any given stage. Moreover, the properties embedded in these sketches can serve as indicators, elucidating the nuances of students' hierarchical thought processes.

Thus, the optimal timing for using this tool would be during sketching sessions, critiques, or reflection periods in the design curriculum. Teachers can employ it as a reference point, both for guiding students and for interpreting their work. Additionally, as students become more familiar with the taxonomy, they too can leverage the tool for self-assessment, gauging their progression and areas of improvement in hierarchical thinking.

## 4. DISCUSSION AND CONCLUSION

In the evolving landscape of design cognition studies, hierarchical thinking has been noted as a significant driver in the iterative design process, with its roots tracing back to Hierarchy Theory (Allen and Star, 2017; Medland, 2007). Existing pedagogical models such as Gero's (1998) Function Behaviour Structure (FBS) framework and Vermaas's (2009) Model of Conceptual layering have significantly contributed to our understanding of the role of hierarchical thinking. However, the gap between design cognition and the use of design representations signals an opportunity for improvement in pedagogical practices. More specifically, our research seeks to bridge this gap, leveraging the principle of hierarchical thinking, and the newly proposed teaching tool provides a tangible method of developing teachers' and students' meta cognitive awareness of the externalisation of their designerly thinking, particularly those associated with part-whole and implementation hierarchical thinking (Visser, 2006).

Hierarchical thinking, as proposed by Visser (2006), forms the backbone of this teaching tool. It serves as a bridge for educators and their students to connect their design intentions with the representational embodiment. By providing areas for focus, this tool can help educators to guide students through the iterative design process, utilizing different sketch types at each hierarchical level. The emphasis on external representation of thoughts through sketches aligns with insights from previous research, stressing the importance of external representations in fostering self-reflection and self-expression (van der Lugt, 2005; Johnson, 2002).

Practical implementation of the teaching tool in real-world classroom settings does pose some challenges. For example, it requires educators to be cognizant of each students' representational capability (Welch, 1998). Modelling the various levels of detail and implementation requires specific expertise that needs to be learned and taught throughout the design process. This expertise isn't just limited to technical proficiencies like technical drawing but should also encompass foundational skills such as sketching and model making (Delahunty et al., 2012). Neglecting the latter can lead to a generation of designers proficient in execution but lacking in innovative thinking. As such, this places extra-curricular time demands on teachers and learners. Furthermore, committing to fostering hierarchical thinking during designing requires educators to delve deep into the nuances of the design process, valuing each step and not just the outcome. It's not just about the end-destination, but the entire journey of designing, emphasizing the essence of sketching and iterative processes which foster creativity and flexibility (Kimbell & Stables, 2008). This nuanced approach contrasts starkly with traditional design portfolios where design representations are often predetermined for assessment purposes.

Notwithstanding its promising implications, our research and the proposed teaching tool present some limitations. The taxonomy of sketches, their corresponding hierarchical levels, and their

influence on student design thinking need further validation in diverse educational contexts. Future studies aim to investigate the graphicacy related skills required to think in designerly ways. While hierarchical thinking provides a cognitive structure that guides the design journey, it is graphicacy—the ability to interpret and produce graphical representation—that brings this cognition to tangible fruition. It's crucial to investigate the symbiotic relationship between these two entities. How do various graphicacy skills correlate with different levels of hierarchical thinking? Does a more advanced graphicacy capability enhance one's ability to navigate the complex layers of design thought? By delving into this interplay, we can better understand the foundational competencies students require to effectively engage with the multifaceted hierarchical levels of design thinking. This insight can significantly shape pedagogical strategies, ensuring students are not only mentally equipped but also technically skilled to traverse the design landscape. Also, the tool's effectiveness in enhancing design outcomes warrants empirical testing through longitudinal studies. Yet, as suggested by Haupt (2018) and Visser (2006), we believe that our work provides a pivotal step towards a more holistic understanding of the design process, sparking further exploration and innovation in design education.

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