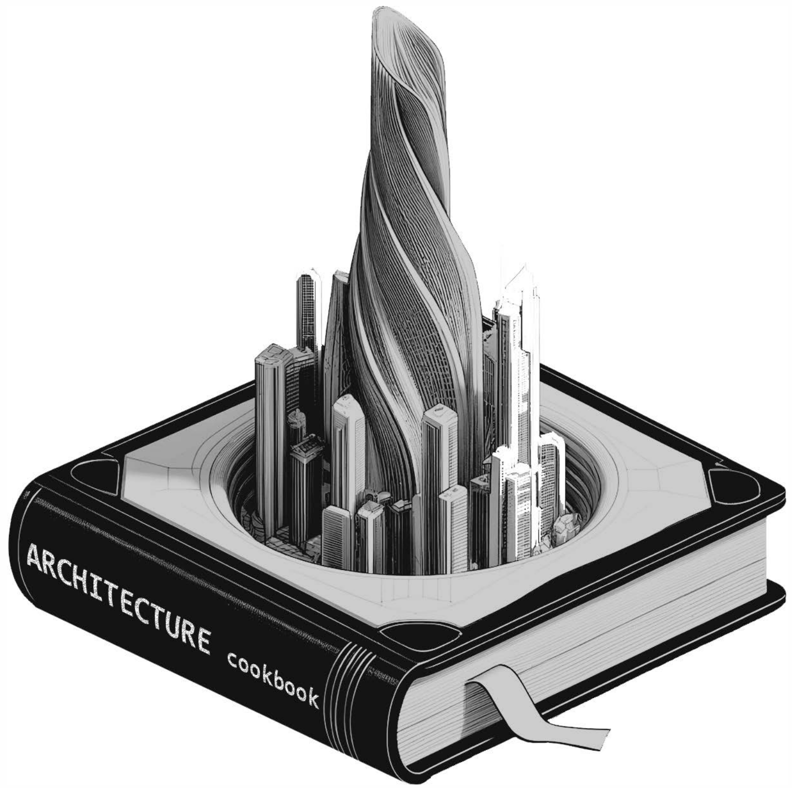
THE IMPACT OF INFORMATION RETRIEVAL IN ARCHITECTURAL DESIGN

Cognitive strategies for navigating Parametric Design Environments

T. Dissaux



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This thesis investigates the impact of information retrieval on architectural design, an area with limited prior research. In today's world, where architects face an overwhelming amount of information and rapidly evolving software, effective information retrieval is crucial for lifelong learning. The study explores the intricate interplay between design, tools, and information retrieval, with a focus on parametric design environments in architecture. By integrating design theory, human-computer interaction, affordance, and cognitive load theory into a multidisciplinary conceptual framework, this research examines how parametric tools influence information retrieval and design processes. Observations from educational settings, where students employ diverse information strategies for autonomous learning, reveal behavioral patterns that are likely to manifest in professional practice. The findings suggest that digital tools profoundly influence novice designers' information retrieval and design choices. This thesis not only highlights the dynamic relationship between architects and their tools in an information-rich environment but also introduces a versatile framework that sets the stage for future research across tools and disciplines.

Submission for the degree of Doctor of Philosophy
Doctoral College of Architecture and Urban Planning

T. Dissaux
2024

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Acknowledgements

First, I would like to express my gratitude to my family. Your support and the circumstances you created have been fundamental in enabling me to reach this milestone. To my wife, thank you for your support throughout this journey. Your feedback has often illuminated how incomprehensible I can be.

I am grateful to my university and faculty for the opportunity and financial support. Your trust in my research and teaching has been invaluable. Thanks to all the students. Without you, there would be no research, and your presence has been a constant source of inspiration. To the field specialists I had the privilege to encounter, the list is long, but I must highlight specific communities: ECAADE, DCC, SCAN, and, MOA. Your support has been greatly appreciated.

Thanks to the LNA for providing a nurturing environment that fostered my growth in both education and research. To my committee, thank you for your regular feedback and for trusting me even when I changed directions during these six years. Special thanks to Salvator John Liotta for being there from the start, always enthusiastic and ensuring that the research would anchor in architecture, to Pierre Leclercq for your invaluable experience, fair reviews, and allowing me to use your name whenever I wanted to connect abroad, and to Stéphane Safin for your rich outsider insights and the writing opportunities.

I am grateful to my jury. Rongrong Yu and Ning Gu, thank you for the opportunity to visit your lab and collaborate. It was an enriching experience that contributed significantly to both my research and personal growth. Thank you to Milene G. Goncalves for taking the time to review this work. Your insights as a pivotal researcher in this field and your critiques are greatly valued.

Lastly, a special thank you to Sylvie Jancart. Your belief in me, your guidance from professional to personal matters, and your encouragement to seize opportunities have been instrumental in my journey. Your support has been unwavering, and for that, I am deeply grateful.

Acronyms

- AD: Architectural Design
- AI: Artificial Intelligence
- CK: Concept Knowledge
- CLT: Cognitive Load Theory
- FBS: Function Behavior Structure
- HCI: Human Computer Interaction
- I_D: Design oriented Information
- I_T: Tool oriented Information
- I^F: Factual Information
- I^P: Procedural Information
- I^C: Conceptual Information
- I^M: Metacognitive Information
- IIR: Interactive Information Retrieval
- IR: Information Retrieval
- K_D: Design oriented Knowledge
- K_T: Tool oriented Information
- K^F: Factual Knowledge
- K^P: Procedural Knowledge
- K^C: Conceptual Knowledge
- K^M: Metacognitive Knowledge
- PDE: Parametric Design Environments
- SAL: Searching As Learning
- SDL: Self Directed Learning
- SRL: Self Regulated Learning
- UI: User Interface
- WM: Working Memory

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1 Introduction

The purpose of this chapter is to provide the reader with contextual markers, thereby framing the rationale behind this thesis. It lays the foundation for exploring and identifying the challenges of information retrieval in architectural design. Initially, the chapter outlines the global context of the research, highlighting societal challenges precipitated by the advancement of digital technologies, particularly information systems, within and surrounding architecture. Subsequently, it discusses the theoretical frameworks and justifies the development of a conceptual framework to study this domain. Lastly, the chapter presents the structure of the thesis and details the methodology employed to address the identified issues.

1.1 Context

In the modern era, information is not only abundant but has also become ubiquitous, significantly influencing professional fields and personal behaviors. This transformation is particularly evident in architecture and more broadly in design, a discipline that has been reshaped by the exponential growth of information and digital tools. The impact of this information-rich environment on architectural design can be observed on two main levels: the embedding of information within the architectural design process itself, and the complexities of digital tools that necessitate ongoing information retrieval.

The expansion of internet accessibility and its integration into daily life and professional practices underscore the ubiquity of digital connectivity. The internet has become increasingly available, facilitating an endless stream of information that architects must navigate (Poushter, 2016). This online connectedness affects behaviors and social interactions, impacting how information is sought and utilized in architecture (Barker, 2009; C. S. Lee & Ma, 2012; Perloff, 2014; Valkenburg et al., 2006). While social media is one vector of this digital engagement, offering both inspiration and potential for distraction, it is merely an example of the broader implications characterized by user interaction and content generation (Kaplan & Haenlein, 2010; Runco, 2015). The challenge for architects lies not only in accessing this vast array of information but in harnessing it in their designs.

Despite the critical role of information in architecture, research exploring how architects' information behaviors influence their design processes is sparse. More understanding is needed on how architects manage and integrate digital content into their design work (Campbell, 2017; Makri & Warwick, 2010; Meyer & Fourie, 2018).

The advent of the 21st century signaled a new era of technological requirements, with architects facing an increasing need to master complex digital tools and information systems (Niu & Abbas, 2017). Oxman discusses this in the context of the growing demands for knowledge across various software platforms, which necessitates a new breed of digital specialists. These specialists are adept not only in traditional design skills but also in the customization and operation of advanced digital systems (Deutsch, 2019; Oxman, 2008). Angulo further emphasizes the close relationship between digital design and information technology, underscoring the continual evolution of this domain and its influence on the conventional modes of teaching and learning in architecture (Angulo & Vermillion, 2012).

With these technological advances, there is a growing consensus among academics on the need for a shift in architectural education towards fostering lifelong learning and independent learning capabilities. As Angulo notes, the increasing specialization and complexity in architecture make it challenging for academic curricula to encompass all aspects of modern architectural practice. The emphasis is on developing strategies that not only encourage design thinking but also empower students to manage their learning paths effectively (Angulo, 2007).

The landscape of architectural design is most likely shaped by the digital and informational shifts of the modern age. As architects navigate these changes, integrating effective information retrieval strategies becomes crucial. Despite the apparent necessity of these strategies, there remains a significant gap in the research, particularly concerning how digital tools and the ubiquity of information influence architectural design and process efficiency. In response to this, the thesis proposes a conceptual framework aimed at bridging these gaps. I will provide a structured approach to exploring the intricate interplay between design, tools, and information retrieval.

1.2 Conceptual Framework

This thesis proposes the construction of a conceptual framework to delve into the complex aspects of information retrieval in the early stages of architectural design. Given the interdisciplinary nature of this topic, a multidisciplinary approach is required to achieve a more comprehensive understanding. Existing frameworks, while providing valuable insights, often remain confined to specific subsets of design activities. Thus, this work aims to develop a broader conceptual framework that integrates various theories and concepts from multiple disciplines to address the intricacies of information retrieval in architecture.

A conceptual framework is understood as a network of interlinked concepts that collectively provide a comprehensive understanding of a phenomenon. These concepts support one another, articulate their respective insights, and establish a framework-specific philosophy. Adopting Jabareen's (2009) definition of a conceptual framework, the study emphasizes its role in framing and understanding complex interactions within a given field.

The construction of the conceptual framework employs a metasynthesis approach, integrating findings from various qualitative studies to generate new interpretations and concepts. Additionally, ontological and epistemological assumptions are drawn from different theories and concepts, enriching the framework's depth. Qualitative methods are employed to explore these complex interactions. Through induction, derivation of concepts from data, and deduction, this methodology facilitates a deep understanding of the relationships between different concepts within the framework.

The conceptual framework developed draws upon Interactive Information Retrieval, which views information retrieval as a sense-making and thus learning activity that transforms information into knowledge. This transformation is central to understanding how architects interact with and utilize information throughout the early stages of the design process. Additionally, the framework incorporates the concept of generativity, a necessary condition encapsulating Concept Knowledge theory, which considers knowledge within design. The Function Behavior Structure ontology is employed to depict internal design processes and how they are influenced by new information.

Inspiration is treated as the explicit model of information retrieval within a design activity, guiding the search and selection of information independent of the tools used. This model clarifies how designers approach and utilize information as part of their design of architectural spaces. Moreover, tools are integrated as a factor of information retrieval. To further consolidate the tool aspect within the design process, the concept of affordance is introduced to describe the interplay between design and tool knowledge and their extension through information retrieval, resulting in the architectural design space.

Interactions within the design task environment have led to the creation of an 'affordance space,' predicated on the assumption that generativity is a foundational condition for design. This space is shaped by continuous engagement with tools and design materials that support the design process. Cognitive load theory is integrated into the framework, recognizing that the effort involved is a significant factor across all theories to consider in designers' behavior when searching for and processing information during the design process. This integration highlights the cognitive challenges faced by designers and the need for tools that support efficient information management.

In summary, the concept knowledge theory functions as the organizing structure within the framework, delineating information retrieval as an extension of knowledge and mapping the cognitive processes in design as described by the Function Behavior Structure ontology. It also takes into account the influence of design tools. This structure facilitates a detailed examination of the reciprocal impacts between these elements and their collective effect on the overall design process. Eventually, it offers the basis of a model that can depict explicitly the variables or factors involved (see Figure 1.1). By systematically exploring these interactions, the framework seeks to deepen the understanding of how retrieved information shapes architectural design practices and outcomes.

By providing a nuanced understanding of information retrieval in architectural design, the framework aids practitioners in navigating the complexities of digital tools and information-rich environments. The development of this conceptual framework represents a step towards theorizing the multifaceted interactions between design, tools, and information retrieval, setting the stage for future research and practice to enhance the efficacy of architectural design processes in the information age.

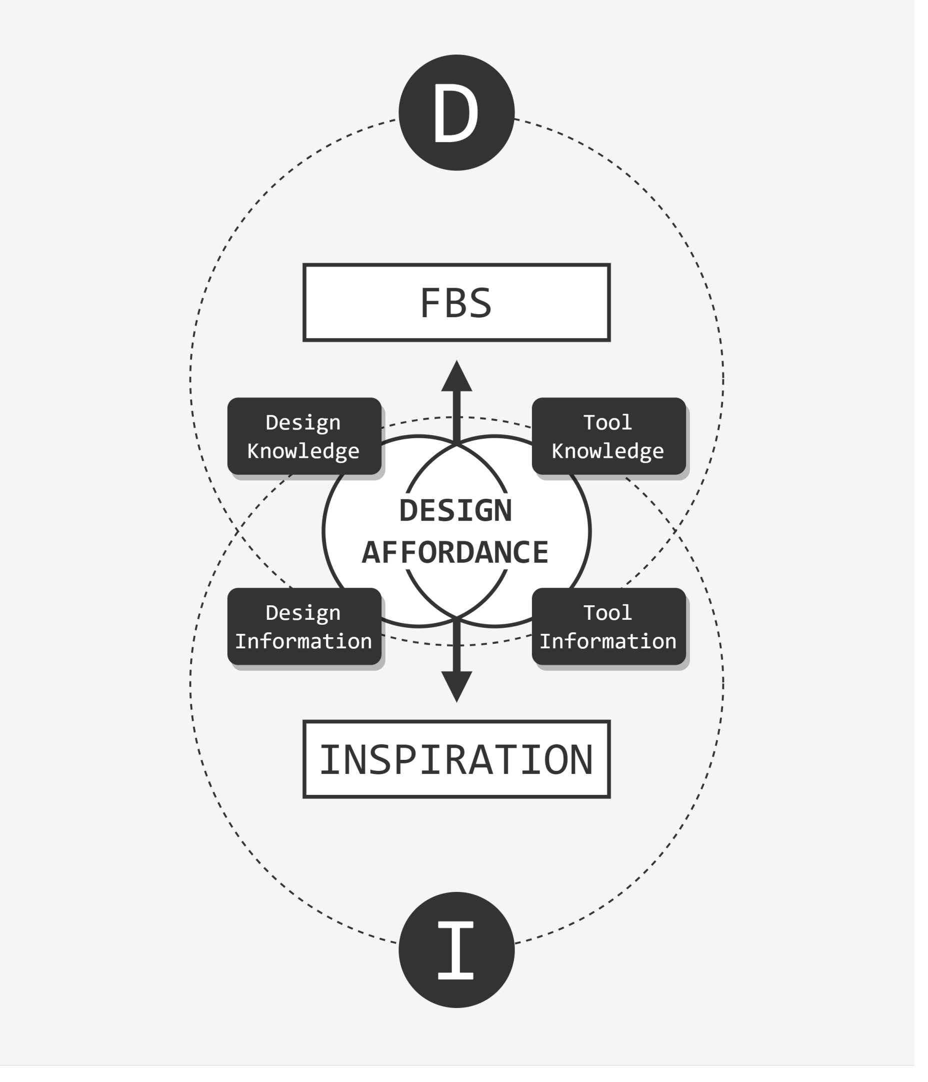


Figure 1.1: *The conceptual model illustrates the interplay between the design process (D) and information retrieval (I), highlighting their roles in architectural design. The design process is informed by cognitive processes, as depicted in the Function Behavior Structure (FBS) ontology, while information retrieval is guided by the inspiration process. Central to the model is the "design affordance space," which represents the landscape of possible designs that emerge from the intersection of design and tool knowledge. This space encapsulates the potential for expanding both design and tool knowledge, thereby broadening the range of achievable designs.*

1.3 Motivation

The primary aim of this research is to investigate the impact of information retrieval in early stages of architectural design. To address this aim, the thesis develops the conceptual framework described earlier as the foundation for research. This framework is tailored to capture the nuances of information retrieval in early stages of design, and takes into account how architects engage with tools as part of their information retrieval. It provides a structured approach to examine the interplay between design, tools and information and the resulting cognitive strategies employed by architects.

This conceptual framework is then applied through the specific case of parametric design and architecture students. The focus on parametric design environments is driven by their complexity and the unique demands they place on information processing and decision-making in design tasks. By focusing on architecture students operating within parametric design environments, the study aims to reveal patterns and strategies in information retrieval that are indicative of broader trends in architectural education and practice.

The central hypothesis of this study posits that due to the complexity of parametric tools, novice users will heavily rely on information retrieval related to the tools, which will subsequently guide design decisions. This focus on tool-related information is hypothesized to influence key design processes, such as the reformulation of design concepts and the application of mental saving strategies. These strategies, in turn, shape how novices use information to guide their design processes.

While the immediate focus is on parametric design environments, the conceptual model developed is intended to be applicable to various design settings involving different tools. This flexibility will allow the framework to explore different approaches to design that require varying degrees of information retrieval related to both design and tool usage.

Ultimately, this thesis aims to provide a foundational basis for future research into information retrieval in architectural design. It seeks to contribute to a deeper understanding of how information retrieval, or the lack thereof, shapes design outcomes, thereby informing both education and practices.

1.4 Significance

This thesis proposes a conceptual framework that offers new foundation for developing a structure to investigate the role of information retrieval in the early stages of architectural design. Given the vast amounts of information architects must manage, which can impact the cognitive pathways they use for designing, this focus is particularly relevant.

It is widely acknowledged that early decisions in a project are the most influential, and understanding how information influences these decisions is crucial. The early stages of design are critical as they set the foundational directions for projects, and raising awareness about how information shapes these early decisions is essential. Eventually, those implications affect the users of the final spaces, the neighborhood, and broader environmental issues.

Furthermore, this study draws attention to the tools used in design. This indirectly addresses the dominance of software firms in the digital tool market, fueled by media that often promotes information about the tools within their intrinsic limitations. This debate follows a critical discussion on software monocultures and their impact on architectural practice (Lynn & Gage, 2010).

> *"Simply stated, one of the largest land-covering products that humans produce, architecture, is now more than ever a vast monoculture of forms. Our dominant architectural software packages produce this through their very genetics" (Lynn & Gage, 2010).*

Research has overlooked how the availability of design tool-related information can drive this impact, which is increasingly relevant given the growing complexity of software tools. This work suggests that it is not merely the tools themselves but the information available about these tools that demands further investigation. There is a growing concern about the reliance on specific tools driven by statistical inference, which not only shapes architectural design but also the choice of tools themselves. For instance, selecting a tool with substantial community support might seem prudent, but that support can be statistically skewed towards certain design typologies.

To illustrate the influence of information, this research examines parametric design environments, known for their complexity and reliance on accessible information. These environments require continuous learning and adaptation to new knowledge therefore exposure to information. However, as parametric design might raise questions regarding the reliance on information retrieval, the lack of it when using other tools might equally be investigated as a potential tool bias.

In essence, this thesis sets the groundwork for studying architects' behaviors in their interactions with both information and tools. It initiates a conversation on how these elements influence architectural design and the broader implications for the field. By examining these dynamics, the study contributes valuable insights to the architectural community, encouraging a more informed and reflective approach to the use of information and indirectly tools in architectural practice.

1.5 Plan

The thesis is structured as follow, beginning with a literature review. This section presents all theoretical frameworks and concepts utilized in constructing the conceptual framework. It includes the progressive building of a visual model that illustrates these concepts and their interrelationships, establishing the foundation upon which the conceptual framework is developed.

Following the literature review, the methodology and research design section outlines the design experiment focused specifically on parametric design environments with architecture students. The methodology is meticulously derived from the theoretical bases explored in the literature review, ensuring that the research design is robust and well-grounded in established theory.

The results of the experiments are presented, analyzing data collected through three distinct methods over a two-year period that directly correlate with the developed model and its depicted variables. This analysis aims to provide a thorough understanding of the information retrieval strategies observed and their effectiveness.

Subsequently, the discussion section delves into the specifics of parametric design environments and their impact on architecture students as articulated by the developed model. It examines the implications of the findings and how they relate to the theoretical framework and hypotheses posited in earlier sections.

The thesis concludes with a chapter that revisits the primary aim of the research—to investigate the information retrieval strategies employed during the early stages of the design process within Parametric Design Environments and potentially other tools. It also outlines the potential for further research and improvements upon the proposed conceptual framework. This final section synthesizes the findings and discusses their broader implications for architectural education and practice, highlighting possible directions for future inquiry.

2 Literature Review

This chapter examines the existing research surrounding information retrieval in architecture. The review begins by exploring general concepts of information retrieval, emphasizing the transition from data to knowledge and the role of interactive retrieval systems.
Subsequent sections delve deeper into the specificities of information within the design process. Discussion on generativity highlights the intrinsic link between information retrieval and design. Selected models of design are used to understand how theoretical frameworks support practical outcomes in architecture. Additionally, the influence of information as inspiration is analyzed, considering how architects define, search for, and select information during the design process. The role of information systems, including the emerging use of AI in design, is also assessed.
The chapter further explores the tools, from traditional methods like sketching to modern complexities introduced by digital culture. Those complexities are illustrated through the scope of Parametric design chosen as the archetype of digital culture in architectural design. The concept of affordance is then introduced to deepen understanding of tool interactions as a crucial factor in the design process.
Concluding the review, cognitive load theory is advanced to address effort. The implications are discussed, framing how these elements significantly impact information retrieval. This literature review sets the stage for investigating the nuanced interplay between architecture, information retrieval, and tools, guiding the subsequent methodological exploration.

2.1 Information in Architecture

Information is integral to architectural design, yet there has been a surprising lack of research on how architects manage, understand, and utilize this information in their work (Makri et al., 2019; Makri & Warwick, 2010). Although architects play a key role in converting information into meaningful designs (Shaaban et al., 2001), the poor research effort has not adequately supported their information-related tasks. This includes developing tools to aid their work or providing training on managing information effectively. This gap in research and support affects the profession's capacity to leverage information optimally in the digital age.

Makri and Warwick (2010) highlighted in their comprehensive review that prior to their 2010 analysis, research on how architects find, interpret, and use information heavily focused on traditional, paper-based sources like journals and magazines, specially in the late 20th century. This was a time before the widespread adoption of the Internet and before digital tools became prevalent in the architectural sector. Despite the significant opportunities and challenges introduced by the Internet for design professionals, the early interactions with this medium were markedly different from today's digital engagement. The scarcity of research in this area underscores a critical gap in understanding and supporting architects' evolving information needs in the digital era.

In the 1970s, Goodey and Matthew (1971) conducted a survey in the UK to understand how architects were using information. Their findings revealed that 57% of the offices regarded research literature as a main source of information despite the fact that information was not as instantly available as it is today and had to rely on print and post offices. They also described a curation process happening in the office where all pieces of information were passed around the office primer to be catalogued. However, this process was also described negatively as it hampered practical information from being available at the right time. Additionally, they observed it was common for architecture offices to have a favorite set of references that would be used extensively.

Snow's (1975) investigation into architects' information requirements reveals a clear preference for easy access to technical and product information, often constrained by inadequate libraries and complex information systems. The study highlights the necessity for enhanced information services and specialist support within architectural practices. Eventually, she stresses the importance of integrating information retrieval into both architectural education and practice, to enhance decision-making and problem-solving skills during the design process.

Powell and Nichols (1982) conducted a study to investigate the information needs and information-seeking behavior of architects and engineers in their daily design work. Their findings showed that architects only sought new information when faced with a significant design problem, while relying on past experiences for other routine design problems. The study also revealed that research documents were not designed to be easily exploitable by designers, resulting in a lack of use by architects. Similar to Goodey and Matthew (1971), the authors found that personal information collections were prevalent among the interviewees, with 95% keeping a limited selection of product data within reach of their drawing boards.

Mackinder (1983) argues that private information collections make it quick for architects to refind information, and architects often collect trade publications because they are comprehensive and well-illustrated. She suggests that the ideal information for architects is “brief and visual,” asserting that architects show a lack of enthusiasm for text.

The advent of the Internet opened new doors while presenting challenges for architects and designers, though initial interactions varied significantly from contemporary experiences, alongside a shift in user preferences. In a study conducted by Rhodes (1998), it was found that studio designers, including architects, interior, and product designers, did not use the Internet regularly because it failed to provide the “right kind of information” or provided “just too much information.” Instead, these designers preferred magazines and journals and conversations with colleagues.

A little later Elliot’s work (2001) described all the shortcomings of Web search by proposing implementations that incidentally are well established nowadays like filters and suggestions. She found that architects made collages in the early stages of design to understand the relationship between parts of a form and the materials they have chosen to work with and to learn about how structures can be put together. Additionally, she found that sketching and image browsing were tightly coupled activities for architects and suggests that one electronic environment should allow architects to do both. Elliott also found that looking at images was “a key part of starting a design project” and that sharing images with colleagues was important, particularly in the early phases of design. However, she found that none of the four architects interviewed used the Web to acquire these images. Some of the reasons given were, again, that it was too time-consuming, too difficult to know where to look, and too difficult to find things even when the architects know they are there. So even with the advent of Internet Snow’s (1975) stays relevant.

Bennett (2006) argued that students were more interested in items fostering original observation through accidental discovery, rather than the more traditional approach to research, which was a more spontaneous approach. However, there were controversies between students and professionals, and the timeline needs to be considered to understand the context. Rhodes'(1998) earlier also argued that professionals may not want to be surprised anymore. There may also be a tendency towards "satisficing behavior" where architects agree on processing habits that are specific to their office.

In more recent years, despite the growing impact of the internet on everyday lives, there has been some limited research into information behaviors in architecture, including the work of Makri and Warwick (2010). Their study looked at how architecture postgraduates find and use information in design projects. The study found that students primarily search for images and sometimes documents, and more surprisingly videos. Before that videos rarely appear in research suggesting new path of research. Subsequent research has corroborated since the observations made by Makri and Warwick (Campbell, 2017; Meyer & Fourie, 2018).

The evolution of information search and usage in architecture over the years can be categorized into three main phases: Pre-Digital, Transition to Digital, and Digital Integration. In the Pre-Digital phase, the reliance on physical media and personal collections was paramount, with Goodey and Matthew (1971) and Mackinder (1983) highlighting the use of research literature, trade publications, and the importance of visually concise information. The Transition to Digital phase saw architects grappling with the new digital tools and the internet, with Rhodes (1998) noting the initial reluctance to adopt online resources due to their overwhelming nature and inadequacy in providing the right kind of information. Elliot (2001) further emphasized the need for better web search tools, which were later on addressed by developments in internet technology. During the Digital Integration phase, the focus shifted towards leveraging the internet more effectively, as seen in the work of Bennett (2006), who observed a preference for spontaneous discovery among students, and Makri and Warwick (2010), who documented the increasing reliance on diverse digital resources including images, documents, and videos.

The relationship architects have with information has transitioned from a reactive approach, seeking out information only when confronted with problems, during a time when access to information was challenging (Powell & Nichols, 1982), to a more integrated and proactive use throughout the design process, facilitated by the ubiquity of digital information (Lorenzo & López Chao, 2021). This evolution signifies a shift from a reliance on traditional resources to a strategic interaction with digital platforms, highlighting the dynamic relationship between architectural practices and the continuously evolving information technology landscape.

Makri and Warwick's (2010) study was pivotal as it introduced information seeking behavior models, specifically Ellis'(1989) behavioral model of information seeking. Despite being more focused on developing search tools, this theoretical model bridges information science theory and user-centered design and laid the foundation for behavioral approaches in information retrieval in architecture. As noted by Makri and Warwick (2010), previous studies have rarely identified information use and communication behaviors, which are key aspects in architectural design where information must feed into a design solution and later communicated to other agents of the project.

Across the various studies into information search and use within the field of architecture, researchers have drawn upon a diverse array of information types to understand and describe architects' behaviors. This includes traditional media such as books and journals, evolving digital resources like online databases and digital imagery, and increasingly, multimedia content such as videos and interactive tools. The variability in information types used reflects the multifaceted nature of architectural work, which requires a blend of technical knowledge, aesthetic judgment, and practical considerations. Acknowledging the diversity of information not only enriches our understanding of architectural practices but also highlights the adaptive strategies architects employ to navigate the information-rich digital landscape. However, this diversity also presents significant challenges for researchers attempting to analyze and cross-reference data, complicating efforts to develop a cohesive understanding of architectural information use.

Despite extensive research into information-seeking behaviors within architecture, there remains a noticeable gap in studies explicitly addressing Interactive Information Retrieval (IIR). IIR focuses on evaluating users' interactions with interactive retrieval systems and their satisfaction with the information obtained. This oversight is particularly significant given architecture's inherent multidisciplinary nature.

Considering the scarcity and dated nature of research on information retrieval within the context of architectural design, this chapter aims to establish new theoretical foundations. The objective is to create a robust conceptual framework that rigorously examines the impact of information retrieval on the architectural design process in early stages of design. By introducing of a series of concepts, the methodical construction of the corresponding model not only addresses the current gaps in research but also provides a comprehensive understanding of how architects interact with information. This model will serve as the basis for subsequent discussions, offering insights into the intricate relationship between information retrieval strategies and architectural design.

2.2 Information and Information Retrieval

In the literature dedicated to design, architecture has already been studied from the perspective of information processing (Love, 2000). Architects access, filter, and interpret information through a personal prism of abstraction, influenced by individual beliefs and values. These interpretations then serve as a basis for manipulating and transforming information during the design process (Shaaban et al., 2001). In the era of the Internet, marked by unprecedented access to an abundance of information, architects find themselves managing significant information overload (Atman et al., 1999; Court et al., 1993; Prabha et al., 2007; Wulff et al., 2000). Despite this, limited research has explored the methods architects employ to access, interpret, manipulate, and utilize information in their design process or how to support these activities effectively (Makri et al., 2019; Makri & Warwick, 2010).

In the context of architecture, the integration of information seems essential for decision making but also, in a fast evolving world, continuously updating knowledge. Information media and sources have been mentioned yet information and its role in the design process are never clearly defined in the architecture literature. To address this gap, this research will ground its theoretical framework in well-defined concepts from Interactive Information Retrieval (IIR) and eventually Human-Computer Interaction (HCI) given ominous digitalization of information. This approach aims to provide a clearer understanding and support for information retrieval processes in architectural design.

2.2.1 Data, Information, Knowledge

The distinction between data, information and knowledge is a pivotal concept, yet these terms are often mistakenly used as synonyms, causing confusion in their conceptual understanding, as noted by Hicks et al. (Hicks et al., 2002). Building upon the delineation by Court and colleagues (Court et al., 1995), as refined by Howard (2008), "data" is characterized as discrete facts or details. When contextualized, these data transform into "information." This transformation involves pairing the raw data with a meaningful context and it is conveyed through various mediums like text, graphics and symbols. "Knowledge," in contrast, is embodied in an individual's capacity to comprehend and skillfully apply information in specific scenarios. This capacity stems from an intricate knowledge integration process. So in short, Information is stored in various sources and can be shared, while knowledge is processed information that has been integrated into one's knowledge structure (Howard, 2008; Kintsch, 1998).

Hicks et al. (2002) suggest that the genesis of knowledge encompasses two integral facets: knowledge processes and knowledge elements. Knowledge elements emerge from knowledge processes, which in turn are activated by an individual's engagement in understanding, assimilating, and applying both information and pre-existing knowledge elements (see Figure 2.1). This dual aspect of knowledge creation aligns with Marsh's (Marsh, 1997) perspective that knowledge is not merely an accumulation of information but the result of assimilating relevant information within a specific frame of reference, emphasizing the evolutionary nature of knowledge as it transitions from data to a refined, contextually grounded understanding. Marchionini (1996, 2006) further describes the information seeking process as a means to change one's state of knowledge while Neuman (2021) describes the use of information as fundamental building block for learning in the "information age."

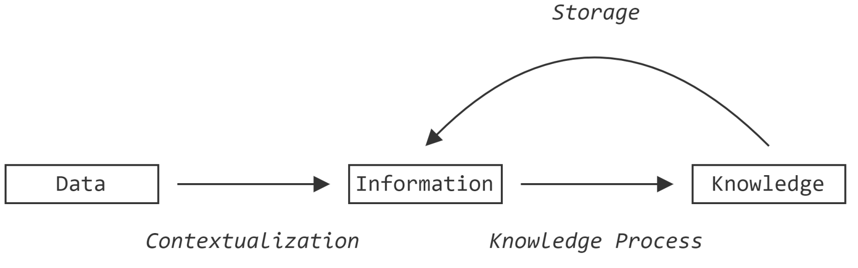


Figure 2.1: *Relation between Data, Information and Knowledge according to Court et al. (1995)*

Furthermore, Hicks et al. (2002) highlight the role of memory in this process. They note that while information can be stored as knowledge elements in long-term memory, recalling specific pieces of information that are not frequently used can be more challenging than retrieving new information. One example is that recalling the colors of the rainbow may require more effort than retrieving the information from the Web. Similarly, architects may require more effort to recall intricate design principles learned in the past than to search for this information online. This understanding underscores the importance of efficient knowledge management in professional practices like architecture, where the ability to quickly and effectively access and apply knowledge can significantly impact the design process.

2.2.2 Interactive Information Retrieval

The shift from traditional "closed" libraries, characterized by intermediary-controlled access, to "open" libraries, facilitating direct interactions between researchers and information, marks a profound shift in the accessibility of information. This shift can be traced to the advent of computerized information retrieval systems within the realm of human-computer interaction (HCI), which effectively merged the disciplines of computer science and library and information science. This merger underscored the necessity for a novel analytical approach to understand the dynamic interactions among users, information, and retrieval systems comprehensively. This imperative led to the birth of IIR, a concept that concentrates on the complex nature of these interactions during the search and retrieval process (Belkin, 2010). Notably, advancements in computing have been instrumental in characterizing and extracting information from increasingly large and complex data sets. These advancements have significantly improved the capabilities for indexing, organizing, and querying information, thus fundamentally transforming the information retrieval landscape (Cool & Belkin, 2013).

In parallel with the evolution of information retrieval towards interactive systems, there's an emerging focus on integrating information seeking with learning, signifying a departure from the traditional bibliographic paradigm towards a holistic, learning-centric approach known as the sensemaking paradigm (Dervin, 1992). This approach favors a more comprehensive understanding of information's role in learning, shifting emphasis from mere access to the nuanced processes of utilizing information for learning purposes. Historically, research within this domain has primarily emphasized the role of accessing information as the central component of learning (Vakkari, 2016). This perspective positioned the acquisition of information as the preliminary step in the learning process, somewhat underestimating the depth of interaction between the learner and the information. However, the emphasis has shifted beyond the initial access, highlighting the processes through which individuals select, organize, and engage with information, thereby constructing meaningful outcomes. This change resonates with the idea of knowledge processing, where learning is seen as an active, constructive effort. In this process, information isn't just absorbed; it's transformed into knowledge (Hicks et al., 2002; Marsh, 1997). Sensemaking emerges as a key aspect of this process, acting as a bridge between searching and learning (Marchionini, 2018). This evolution has led to the development of the Search as Learning (SAL) paradigm in the field of information retrieval (see Figure 2.2). (Vakkari, 2003; P. Zhang & Soergel, 2014).

SAL emerges as critical concept. It involves searching for information to understand concepts and their interrelations, thereby gaining a deeper understanding and more effectively structuring and representing a given task. Sensemaking

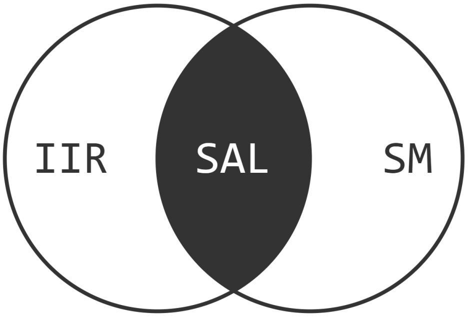


Figure 2.2: *Search-as-learning (SAL) at the intersection of Interactive information Retrieval (IIR) and Sensemaking (SM).*

underscores the creative aspect of the design process where solutions are created rather than found. This concept, adapted from various authors (Dervin, 1992; Qu & Furnas, 2008; Russell et al., 1993), further aligns with Vakkari's design oriented view of the search process as a solution-creation activity (Vakkari, 2010).

Because the aim of searching is supporting learning or investigative activities (Marchionini, 1996), the notion of exploratory search can also be applied here. Exploratory search pertains to information search primarily aimed at collecting and utilizing information for learning (White & Roth, 2009; Wildemuth & Freund, 2012) and further advances the concept of SAL within the sensemaking paradigm. Most Web search activities do not merely consist of simple lookups for specific piece of information but is most often complex and exploratory in nature (Athukorala et al., 2016; Marchionini & White, 2007). Such online search activities, as opposed to simple fact-finding or navigational tasks, are typically open-ended and aimed at sensemaking and understanding of the information retrieved (Vakkari, 2016; Wildemuth & Freund, 2012). Defined by its learning and investigative nature, exploratory search involves general, open-ended tasks often directed at multiple items or documents. Marked by uncertainty and motivated by ill-defined problems, it closely resembles the characteristics of a design problem as defined by Gero (1990). It involves a blend of search and browsing behaviors to navigate, comprehend, and interpret retrieved information, often in conjunction with other cognitive behaviors like sensemaking (Wildemuth & Freund, 2012). Vakkari (2010) also noted the relationship between exploratory searching and sensemaking, observing that the solution to a problem is created, not found.

Rieh et al. (2016) also define search as a learning process and highlights the evolving nature of exploratory search. This approach transcends providing mere search results, focusing instead on aiding users in exploring, navigating uncertainties and learning (White et al., 2006; White & Roth, 2009). This notion of exploratory search is crucial for effective information retrieval, especially in design contexts where the nature of search tasks is inherently complex and evolving.

This framework particularly in the context of exploratory search, is closely linked to information literacy. This concept emphasizes the need for critical skills in seeking, evaluating, and using information, seen as essential for lifelong learning (Brown & Krumholz, 2002; Oblinger & Hawkins, 2006). In the context of a digital world it highlights the importance of architects' digital literacy, especially as search systems often do not inherently support the exploratory nature of searches.

In summary, the SAL framework marks a significant departure from the bibliographic paradigm, emphasizing knowledge construction over simple information collection and storage (Vakkari, 2016). This shift resonates with Howard's distinction between information and its integration into a knowledge structure (Howard, 2008; Kintsch, 1998). The principles of SAL, which are particularly relevant to the exploratory nature of search in design, will be explored further.

2.2.2.1 A&K Taxonomy

Building on the predicates of SAL, Jansen et al. (2009) propose to adapt the taxonomy of Anderson and Krathwohl (A&K) (L. W. Anderson & Krathwohl, 2001), a revision of Bloom's taxonomy used to define learning objectives in education (Bloom & Krathwohl, 1986). A&K's model defines learning objectives using two dimensions: cognitive processes and knowledge type (see Table 2.1). Knowledge in this context should be understood as processed information. For instance, if a task necessitates factual knowledge, the individual should seek factual information to process.

Cognitive processes can be categorized into six levels of complexity from least to the most complex task : remember, understand, apply, analyze, evaluate, and create. A "remember" objective is achieved when the learner can recall or reproduce information exactly as it was presented. An "understand" objective is met when the learner can explain the information in their own words or provide examples of its application. An "apply" objective is accomplished when the learner can use the knowledge to solve problems or perform tasks in a new context. An "analyze" objective is attained when the learner can identify and explain relationships between different elements or ideas. An "evaluate" objective is achieved when the learner can assess the importance or value of different

Table 2.1: *The A&K (Anderson & Krathwohl, 2001) taxonomy for determining learning objectives is a revision and expansion of Bloom's original taxonomy. It classifies learning objectives into two dimensions: the Cognitive Process Dimension (Cp) and the Knowledge Dimension (Kt).*

Kt / Cp	Remember	Understand	Apply	Analyze	Evaluate	Create
Factual	-	-	-	-	-	-
Conceptual	-	-	-	-	-	-
Procedural	-	-	-	-	-	-
Meta-Cognitive	-	-	-	-	-	-

components and prioritize them accordingly. Finally, a "create" objective is met when the learner can develop new solutions to problems or construct novel representations of information. Based on A&K's revision, a design task would fall under producing within the create category. These six levels of cognitive processes provide a useful framework for educators to design and assess learning objectives. This thesis will consider the create category since it relates to the design task but also aligns with the principle of exploratory search.

It is important to stress that the process towards a specific learning objective does not limit to that specific type of task. A&K describe the cognitive processes as combinations of lower complexed processes (L. W. Anderson & Krathwohl, 2001; Urgo & Arguello, 2022). The create task for example is a process that can combine sub-processes such as analysis and evaluate. These processes will actually be described as explicit parts of the process later when addressing design theory.

To build on the cognitive process dimension, understanding task complexity in information search is crucial. Li and Belkin (2008) characterize search tasks by considering external factors, like whether they are self-assigned or imposed, and internal aspects, which include subjective attributes like difficulty and objective attributes such as complexity. Wildemuth et al. (2014) further elaborate on complex search tasks, noting that these tasks often encompass a larger number of subtasks, present more uncertainty about inputs and outputs, and require more intricate mental processes. These factors underline the cognitive complexity of tasks, emphasizing that tasks perceived as more cognitively complex are often considered more difficult, require increased search activity, and result in a broad range of strategies among searchers accomplishing the same task (Capra et al., 2015; D. Kelly et al., 2015).

The second dimension concerns the type of knowledge (see Figure 2.3). The taxonomy identifies four types: factual, conceptual, procedural, and metacognitive. The first three types are related to external knowledge about the world. Factual knowledge refers to discrete, objective information (e.g., what is the capital of Burundi, or, what is the building height limit in a specific area), while conceptual knowledge encompasses concepts, categories, theories, principles, patterns, and models (e.g., What is a capital, or, what is parametric architecture ?). Procedural knowledge is concerned with how to perform a task ("How to cook a risotto?" does not imply possessing or developing knowledge about each ingredient or cooking techniques in general). Ultimately, regardless of the type, it feeds into conceptual knowledge, often referred to as conceptual structure and paralleling the constructivist approach inherent in exploratory search: individuals construct knowledge by actively engaging with and exploring the information. In other words, regardless of the type of knowledge integrated, it ultimately feeds into conceptual knowledge (e.g., by learning recipes through procedural information, one develops knowledge about cooking conceptual knowledge).

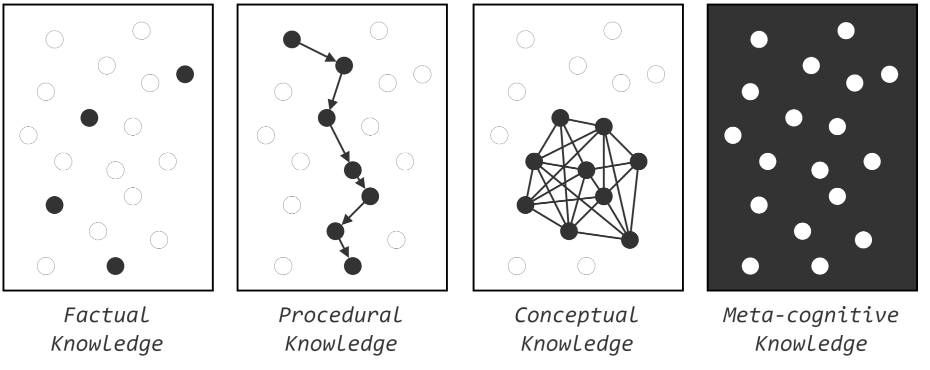


Figure 2.3: *Abstract visualization of different types of knowledge*

Metacognitive knowledge on the other hand plays a distinct role in this taxonomy. Unlike the other types of knowledge that are externally focused, metacognitive knowledge is introspective and self-directed. It pertains to an individual's awareness and understanding of their own cognitive processes. This type of knowledge is particularly relevant in the context of digital literacy in architecture which involves a searcher's ability to not only access and utilize digital resources effectively but also to reflect on their own searching strategies, evaluate their efficiency, and adapt them as necessary (Savic & Bühlmann, 2017). In the digital age, where searchers are inundated with a vast array of information sources, metacognitive knowledge becomes essential. It enables them to navigate through this information landscape selectively and purposefully, critically assessing the relevance and reliability of information, and continually refining their search strategies. Metacognitive knowledge described by A&K aligns closely with other definitions found in architecture research. Angulo (2007) describes metacognitive knowledge as a key factor to autonomous learning in the context of forced lifelong learning. However, to date, there appears to be a lack of studies specifically addressing this type of knowledge within the realm of IIR.

These two dimensions, the cognitive process and the type of knowledge, aim to better define learning objectives in education. However, Jansen et al.'s (2009) use of the taxonomy outside the educational context provides a relevant framework for understanding information retrieval as a learning process. Emphasis is thus placed on the information searcher's (here, the architect's) ability to independently identify and select the most appropriate type of information and to build the necessary knowledge at each stage of their creative process. However, prior studies have primarily focused on the cognitive process dimension, leaving the knowledge type dimension less explored (Urgo et al., 2020).

2.2.2.2 The role of Procedural Knowledge in architecture.

In architecture, though not directly referencing the A&K taxonomy, Lang et al. (1991) underscore the predominance of procedural knowledge in CAD education, noting its high transferability and preference over declarative knowledge. This preference arises because utilizing declarative knowledge, such as knowing which button to press (akin to factual knowledge pertaining to the tool), requires a well-developed conceptual understanding for formulating specific queries.

Conversely, more recent studies using the A&K taxonomy have shed light on the role of knowledge in research in architecture. Vrouwe et al. (2020) have highlighted the significance of conceptual knowledge in parametric design education. Parametric design is a computational approach to architectural design and implies added complexity through an algorithmic way of thinking (Woodbury, 2010). They define conceptual knowledge as the process through which learners form a network of connections among different aspects of factual knowledge. This enables the creation of mental models that effectively organize and distinguish information, reflecting the constructivist approach to conceptual knowledge. They argue this type of knowledge is crucial for understanding the underlying principles and properties of design elements.

In contrast, current research in IIR suggests that although there is a consensus in SAL on ultimately building a conceptual structure when learning, more complex tasks such as "create" elicit different behaviors from autonomous learners. Urgo and colleagues (2020) reported that conceptual knowledge retrieval tasks were more prone to abandonment, took longer, led to less satisfactory results, and were perceived as more difficult than procedure-oriented knowledge retrieval tasks. In the case of create tasks, procedural knowledge was shown to be the preferred type of knowledge that learners sought to integrate.

This preference for procedural knowledge seems evident in the handling of ill-defined problems and unclear objectives, common in exploratory searches and design processes. Urgo et al. (2020) indicate that when faced with undefined objectives, searchers often rely on procedural knowledge due to its clear starting and ending points. Conversely conceptual knowledge objectives seem more amorphous therefore more complex to searchers (Liu et al., 2013; Urgo et al., 2020). Furthermore searchers tend to find it easier to engage in evaluative thinking with procedural information. They often rely on surface-level evidence or heuristics, such as the number of steps involved, the materials required, and the visual complexity, to assess and decide whether to integrate procedures into their tasks. This occurs regardless of the actual relevance or pertinence of these procedures to the task at hand but rather on the perceived difficulty of integration (Urgo & Arguello, 2022).

Similarly, the results Urgo and Arguello (2020) also found investment into Factual knowledge to be less important than procedural knowledge during create tasks. This observation aligns with Lang et al. (1991), who noted the challenges in formulating queries due to a lack of prior conceptual knowledge. While Lang et al. (1991) referred to the context of CAD education, Urgo et al. (2020) discussed computerized search systems. However, it's critical to acknowledge the dynamic interplay with other information sources. For instance, in the context of more complex tasks, Bystrom (2002) demonstrates that searchers show a preference for human sources, which inevitably influences their behaviors on search systems (Borlund, 2013).

While the preference for procedural knowledge in complex processes, especially in create tasks, is well-established, it's crucial to consider the potential impacts of this tendency. Procedural knowledge, due to its clear start and end points, often takes precedence over conceptual and factual knowledge (Lang et al., 1991; Urgo et al., 2020). However, this reliance might lead to what Choi et al. (Choi et al., 2019) describe as "satisficing behaviors" in the search process. Such behaviors involve settling for a satisfactory, yet possibly suboptimal, solution because the user depends on readily available procedural knowledge. The risk here is that searchers and in this case, architects, might prioritize procedural familiarity over exploring more conceptually challenging, yet potentially better design solutions.

2.2.3 Summary

In architectural design, the study of information retrieval has been relatively underexplored, particularly in the digital age. Research in this field has primarily focused on traditional, paper-based methods and hasn't kept pace with the digital transformation that has reshaped information accessibility. This discrepancy in research evolution coincides with the absence of a consistent foundational framework for categorizing information.

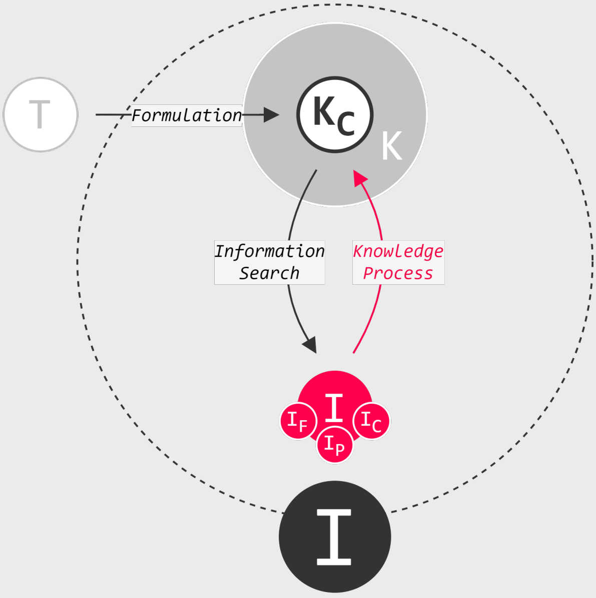
To address the ambiguity in defining "information" in architectural literature, concepts from Human Computer Interaction (HCI) are employed. The distinction between data, information, and knowledge becomes pivotal in this context. "Data" transforms into "Information" when contextualized, and "Knowledge" is the capacity to apply this information in specific scenarios. Knowledge, therefore, is seen as processed information.

The emergence of Interactive Information Retrieval (IIR) reflects the evolution from traditional library systems to more direct, user-information interactions. The shift from viewing information seeking as data collection to recognizing it as a knowledge construction process represents a significant paradigm change. Subsequently, the Anderson and Krathwohl (A&K) taxonomy, revising Bloom's taxonomy, is particularly relevant here. It categorizes learning objectives into cognitive processes, such as create tasks, and knowledge types, providing a framework to understand the transformation of information into knowledge in the architectural context.

Recent studies emphasize the importance of both conceptual and procedural knowledge in architecture education. However, there's a noticeable preference for procedural knowledge in create tasks due to its structured nature and ease of application. This preference, while beneficial in handling well-defined problems, can lead to a reliance on familiar procedures at the expense of exploring more conceptually challenging solutions.

In summary, integrating A&K's taxonomy and HCI principles offers a comprehensive approach to understand and aid architects in their information retrieval process. This approach underscores the importance of converting information into knowledge and raises concern regarding procedural knowledge in architectural design.

Expansion of knowwledge through information retrieval



*Learning objectives are formulated by the searcher based on the task **T** and prior knowledge **K**. The user searches for information according to the types defined in A&K (Factual information I_F, procedural Information I_P or Conceptual Information I_C). Information **I** is retrieved through a knowledge process into a larger network of prior conceptual knowledge K_C.*

2.3 Information in Design

Design theory is a dynamic and multifaceted field that has produced numerous theories and models from various perspectives to address different purposes. Despite the growing recognition of the value of design, particularly in the current manifestation of design thinking, there remain ongoing debates about its logics, foundations, and contemporary value (Cross, 2023). These debates reflect the challenges of dealing with design due to its fragmentation across different professions and the need to resist the influence of scientific fashions (Le Masson et al., 2013). Furthermore, design must continually adapt to changing environments such as the digital age. The design field has struggled to establish a unified identity, with research remaining "cacophonous and without a set of shared problematics" (Margolin, 2010).

At the heart of these challenges lies the very nature of design problems, which are often ill-defined, with incomplete, inconsistent or vague specifications (Gero & Maher, 1993; Goel, 1995). Smithers (1998) highlights that, at the beginning of the design process, the context, constraints, and possibilities are frequently poorly understood. In response to this reality, Wynn and Clarkson (Wynn & Clarkson, 2018) propose a topology of the literature on theoretical models of design, offering a useful categorization to position these models relative to each other. Among this wide range, two models stand out for their relevance to information search in design as they are both based on the notion of knowledge : the Concept-Knowledge (CK) model and the Function Behavior Structure (FBS) model.

2.3.1 Decision, Creativity, Generativity

Design problems are prime examples of ill-defined problems. They begin with specifications that are often incomplete, inconsistent, and/or vague. This is due to a lack of full understanding of the context, constraints, and possibilities at the onset of the design process. According to Gero and Maher (1993), problems can be categorized as either routine or nonroutine. Routine problems are well-defined, with all necessary knowledge available to solve them (Gero, 2000; Maher, 2000). In contrast, nonroutine problems are harder to automate due to the need for modifying constraints and introducing unforeseen variables. These problems require interpretation, reformulation, negotiation, and a focus on meeting stakeholder needs, which sets nonroutine design apart from routine tasks (Gero & Maher, 1993; Goel, 1995; Smithers, 1998).

Historically, design research has focused primarily on well-defined problems, employing rational models aimed at finding optimal solutions. However, such models have been critiqued for oversimplifying the inherent complexities of the design process (Goldschmidt, 1994; Suwa et al., 1998). This critique highlights the importance of recognizing the unpredictable and expansive nature of design solutions, which is characteristic of ill-defined problems. Hatchuel et al. (2018) further explore the nature of design tasks in relation to uncertainty. They argue that design tasks vary in their engagement with the unknown. If "unknown" pertains to uncertainty in well-established design parameters, the task becomes an optimization process, aiming to reduce this uncertainty and align with decision-making under uncertain conditions. Alternatively, if "unknown" encompasses the exploration of entirely new design parameters, the task expands into uncharted territories, including new scientific findings and technological principles, ultimately, new knowledge.

Hatchuel et al. (2013) introduce the concept of Generativity as a theoretical concept that also offers a distinct perspective from both decision theory and creativity in the field of design. Unlike decision-making, which is grounded in deductive reasoning, generativity involves the formulation of propositions that extend beyond mere deduction from known elements (Hatchuel et al., 2018). Generativity is distinguished from creativity. While creativity focuses on ideation within established knowledge frameworks, generativity encompasses not only the ideation process but also the capability to create one or multiple entities that embody the creative idea (Le Masson et al., 2011).

Generativity is about the capacity to conceptualize and create new alternatives using known building blocks, but in ways that are fundamentally different from any existing combinations. Generativity must therefore comply with the splitting condition. The splitting condition refers to knowledge structures and the idea that a new proposition must be different from all already known propositions (Dehornoy, 2017; Jech, 2003; Le Masson et al., 2016). It requires no determinism and no modularity in the knowledge structure. The absence of determinism means that the new design requires new knowledge that is not directly determined by initial knowledge. The absence of modularity means that the new design is not a modular instance of old designs, but requires new concepts. Hatchuel et al. (2018) propose the example of lego blocks and Erik Johansson's (2007) surreal photography "impossible construction"(see Figure 2.4).
In that example, the standard rules of Lego are transcended to propose something new, utilizing familiar blocks but extending beyond any previously known combinations. The result is a uniquely unexpected structure that breaks free from modularity and determinism.

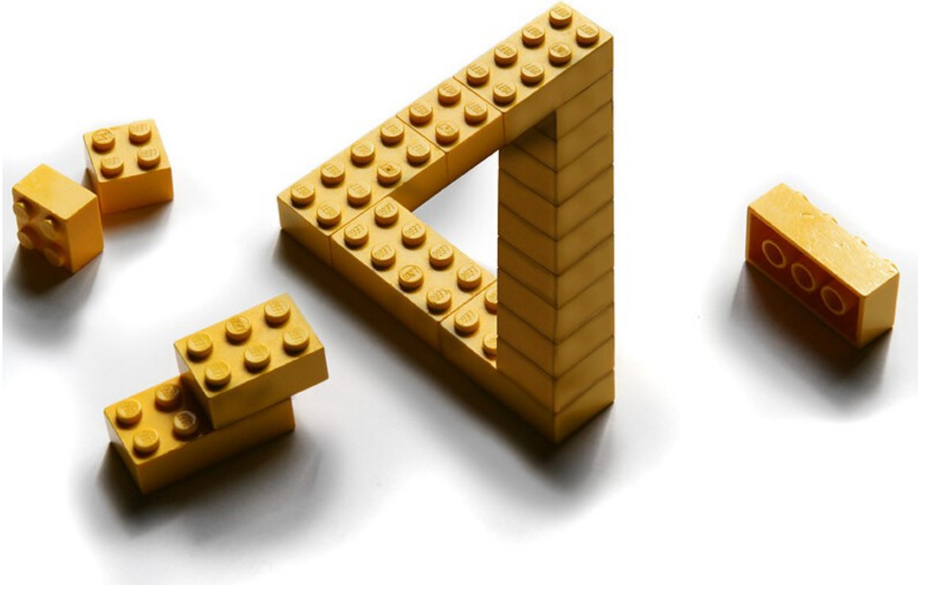


Figure 2.4: *Johansson (2007) escher lego.*

"(...)combining old pieces of knowledge so as to create an artifact that is of course made of known pieces but goes beyond all combinations of the known pieces by breaking the rules of composability. The problem has been transformed, allowing for new avenues of generativity"(Hatchuel et al., 2018).

The splitting condition is a critical property that highlights the value of independence in a knowledge structure. The proposition cannot be deduced from past ones and can add significant dimensions to an artifact. This observation carries significant implications for teaching and learning, especially when considering the integration of knowledge through external means like information retrieval. It highlights the importance of examining the splitting condition in knowledge structures and eventually its potential impact on architectural design.

The relative nature of generativity must also be considered. According to Hatchuel et al. (2018), generativity can exist at varying levels. At lower levels, design problems are addressed within a decision framework, while at higher levels, more generative models of design theory are employed. For example, when studying modularity, one might work with a given set of modules or develop new ones with specific properties that enhance generativity. Similarly, an engineering system can be examined for stability and invariants, or one can study how an engineering system can generate new objects and shapes. In fact, engineering systems can be designed to follow the splitting condition, which enables strong generativity.

A practical example of such a system is the Application Programming Interface (API) of a software program. APIs extend beyond traditional user interface modularity, offering developers direct access to the software's capabilities. This access enables the creation of new functionalities that surpass the original software environment, albeit within the constraints set by the API's architecture. As a result, while APIs enhance generativity by enabling new uses and integrations, they also confine developers to the functionalities that the API provides. This duality illustrates how a design medium can serve as a catalyst for generativity, yet simultaneously impose a higher set of rules. Given that generativity encompasses more than just ideation, its relative nature suggests that the environment can significantly influence the design process.

This theoretical approach challenges traditional views of design, which are often critiqued for their limitations in accommodating the complexities of design tasks (Dorst, 2006; Schön, 1992). However despite those critiques, numerous models of design can account for generativity: General Design Theory (Reich, 1995; Tomiyama & Yoshikawa, 1986; Yoshikawa, 1981), Axiomatic Design (Suh, 1990), Coupled Design Process (Braha & Reich, 2003), Infused Design (Shai & Reich, 2004), CK Design Theory (Hatchuel & Weil, 2003; Hatchuel & Weil, 2009), the Function Behavior Structure model (Dorst & Vermaas, 2005; Gero, 1990), and Zeng's product design theory (Hatchuel et al., 2018; Shai et al., 2009, 2012; Zeng & Gu, 1999).

2.3.2 Models of Design

Reflecting on the insights from the last chapter, it becomes evident that generativity plays a significant role in the context being discussed. Consequently, the Concept-Knowledge (CK) theory emerges as a pertinent framework, having been developed with generativity as a foundational premise by its authors. Nonetheless, it has been noted that concepts akin to those in CK theory have also been embraced within other theoretical frameworks.

In their 2018 article, Wynn and Clarkson (2018) discuss the topology of the literature on theoretical models of design by introducing a categorization to help position the models relative to each other (see Figure 2.5). These categorizations are influenced by the intentions of the designer (Browning et al., 2006; J. F. Maier et al., 2017). The classification framework groups similar models to allow for meaningful comparisons and relationships. Models are grouped based on the characteristics of the targeted situation and the overall objective of the model. The first dimension, scope, ranges from individual cognitive activities to complex development programs. Because this research focuses specifically on early stages of design, only the micro level is considered. The micro level focuses on individual steps (or small groups) of the process and their immediate contexts, as opposed to macro models that address management issues and further development processes in design.

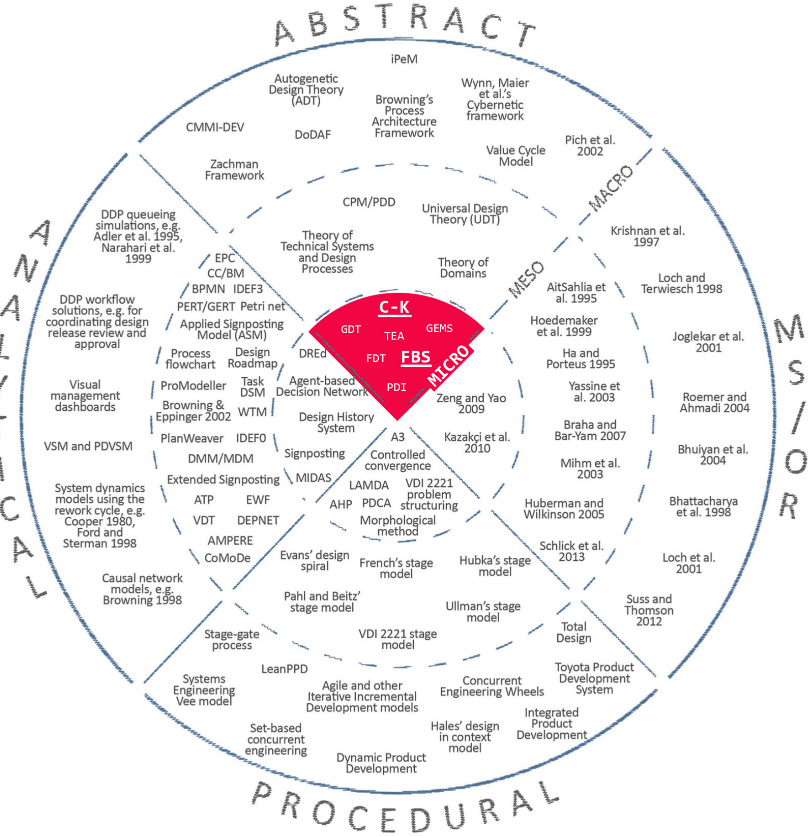


Figure 2.5: *Classification of design process models, highlighting those of particular interest within the micro and abstract dimensions (Wynn and Clarkson, 2018).*

The second dimension relates to the objective of the model. A particular type, called abstract, is focused in theories in the design process. These models focus on forms of reasoning, elementary activities, and/or interesting types, structures, and evolution of knowledge that occur during design. Incidentally, the abstract

Table 2.2: *Concepts used in discretizing Micro-Level abstract level and their associated author(s) from Wynn and Clarkson (Wynn & Clarkson, 2018) and their associated author(s).*

Concept	Associated Author(s)
Designing starts with ill-defined problems	Smithers, 1998
Design problems and solutions coevolve	Dorst & Cross, 2001
Design is partly solution-oriented	Wynn & Clarkson, 2005
Designing creates new parameters and generate new knowledge	Gero, 2000
Designing involves hierarchical structures	Guindon, 1990
Designing is situated	Gero & Kannengiesser, 2004
Designing is progressive and iterative	Wynn & Eckert, 2017

dimension is the only dimension concerned with non-routine problems. The table below presents the key concepts used in the characterization of the Micro-Abstract level, with the authors associated with each concept (see table 2.2).

Ill-defined problems have already been established. Regarding co-evolution, it advances that the design process involves refining together both the formulation of a problem and ideas for a solution (Maher et al., 1996). Co-evolution implies iterativity where solutions inform problem understanding, which in turn refines the solutions. The co-evolution theory is based on principles of creativity as it looks at cycles of ideation however it is based upon a cycle of synthesis and analysis implying an entity needs to be created (or synthesized) in order to be analysed.

Design as solution oriented seems evident as architects and designers are ultimately expected to provide solutions. However, it is intriguing to consider the implications of this solution-oriented approach on what might otherwise be an exploratory search (Kruger & Cross, 2006). Emphasizing solutions can inadvertently foster a deterministic approach that can conflict with the principle of generativity. The challenge, then, lies in balancing the need to provide practical solutions while fostering an environment that encourages generative and exploratory processes.

Situatedness of design relates to co-evolution as each design step impacts the design process. More importantly it considers the designer's available knowledge which implies the ability to access "external knowledge" (knowledge from outside the current known knowledge) and the individual's reordering of knowledge associated with new entities which is essential in generativity (Gero & Kannengiesser, 2004; Hatchuel et al., 2018).

Four theoretical frameworks align with generativity and the design process at a micro abstract level, as shown in Table 2.3: General Design Theory, the Coupled Design Process within Foundational Design Theory, Concept Knowledge (CK), and Function Behavior Structure (FBS). Notably, CK is considered an interpretation derived from the Coupled Design Process, which itself is a generalized approach to General Design Theory (Hatchuel & Weil, 2009). Furthermore, both CK and FBS, along with their underlying models, have gained wider acceptance and are frequently used to structure conceptual, computational, and empirical studies in the field (Agogué et al., 2014; Hamraz et al., 2013; Howard et al., 2008; Yu et al., 2014).

Table 2.3: *Models mentioned in accordance with generativity (Hatchuel et al., 2018) and models in accordance with the micro abstract level (Wynn and Clarkson, 2018).*

Models in accordance with Generativity	Models from the Micro-Abstract dimension
General Design Theory	**General Design Theory**
Axiomatic Design	-
Couple Design Process	**Couple Design Process**
Concept Knowledge	**Concept Knowledge**
-	Production Deduction Induction
Function Behavior Structure	**Function Behavior Structure**
-	Task Episode Accumulation
-	Generate Evaluate Modify and Select

These models notably complement each other: CK (Concept-Knowledge) stands out for its direct incorporation of knowledge expansion, resonating with Interactive Information Retrieval (IIR) and Search as Learning (SAL), a feature less explicitly addressed by the other models. Meanwhile, the FBS (Function Behavior Structure) model distinguishes itself by breaking down the design process into distinct cognitive steps. This approach suggests a structured effort that mirrors the cognitive complexity inherent in create tasks.

2.3.2.1 Concept-Knowledge model

Inspired by the works of Yoshikawa (1981) and Reich (1995), the CK theory focuses on the navigation between two spaces: the knowledge space and the concept space. The knowledge space (K) represents the accessible knowledge repertoire of a designer, while the concept space (C) is a territory of potentialities and unmaterialized ideas (see Figure 2.6) (Hatchuel & Weil, 2009). These spaces are structured and continuously expanding. The K space captures and extends the designers' knowledge, which then serves as a basis for generating new concepts in C. In the C space, designers propose structures based on the attributes of K. By adding or removing attributes, they generate alternatives, resulting in a branching C space. During the design process, when a concept emerges in the C space with undetermined attributes derived from K, it is not initially considered true or false (undecided). However, if all its attributes are evaluated and validated in K, the concept is deemed adequate and suitable for further development. Proposals that do not pass this filter are discarded. Thus, a concept is always relative to K, and its value is determined by its conformity with existing knowledge.

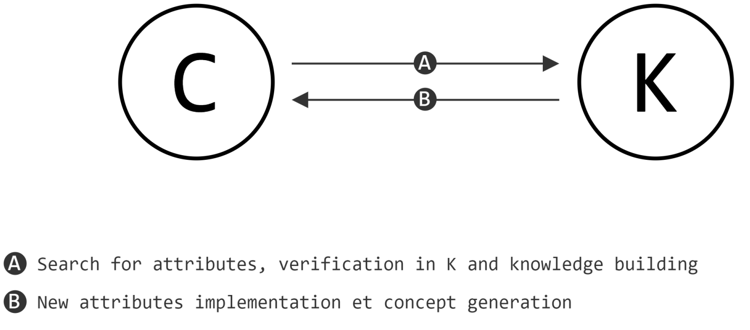


Figure 2.6: *CK model as a foundation for the conceptual model*

The two spaces are in expansion. They generate and test ideas, but not with the same logic. The CK theory sets the framework for a design process that involves refining and expanding an initial concept by adding attributes from the K-space. The two expansive processes are intertwined in CK interactions, with concepts leading to knowledge expansions and vice versa. This approach characterizes different paths of solutions and the pockets of knowledge associated with different sets of solutions.

To capture the various situations and dynamics of design, Hatchuel and Weil (2003) have proposed four operators: C⇒K (*conjunction*), K⇒C (*disjunction*), C⇒C and K⇒K that relate to the aforementioned expansion (see Figure 2.7). The process of design involves generating disjunctions through K⇒C operator, where knowledge elements (K) are transformed into concepts (C). Disjunction implies the subsequent generation of alternatives. Indeed, concepts are not alternatives in themselves but rather potential "seeds" for generating alternatives, thereby expanding the conceptual space (C) with elements derived from knowledge (K) into a tree structure. The development of concepts leads to the creation of new alternatives through processes like partition or inclusion, and these concepts are subsequently re-integrated into the knowledge domain (K) via the conjunction operator C⇒K. This conjunction implies the expansion of knowledge, as it incorporates new concepts from C into K, fueled by the initial expansion of concepts. Thus, these operators not only describe the interplay between concepts and knowledge in design but also highlight the iterative process of expanding the concept and ultimately knowledge, a necessary condition for generativity.

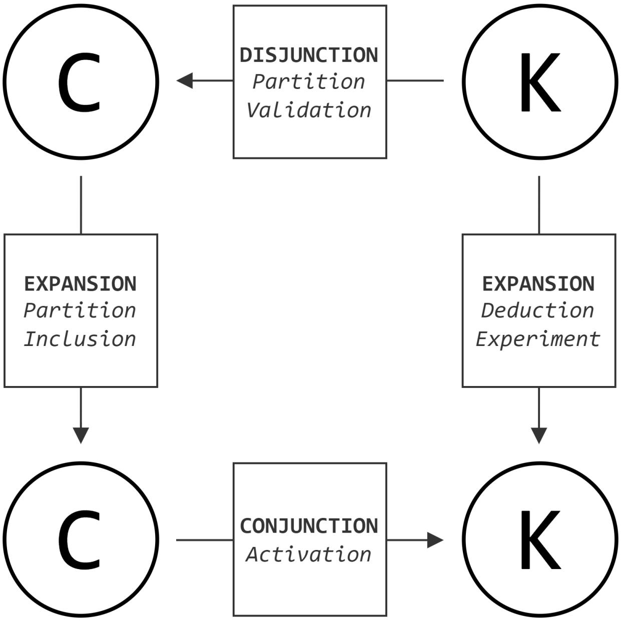


Figure 2.7: *CK operators according to Hatchuel & Weil (2003).*

It is important to note that design cannot be defined without knowledge expansion. The process of transforming concepts into knowledge propositions in K is essential. This has significant implications for information and knowledge retrieval, as simply looking for and using existing knowledge will not result in design activity because it won't necessarily induce a disjunction/conjunction dynamic. Rather, it necessitates the extraction of knowledge and the strategic addition or removal of properties to forge new concepts.

The following example illustrates the CK dynamics (see Figure 2.8). Brun et al. (2016) describe the design exercise of an architect tasked with designing a library. The C space is studied here through a single modality: the drawing which is represented by the subset D (Design Space D). The architect organizes a strategically constructed knowledge space, where each attribute (element in K) is selected, tested, and, if necessary, removed. To facilitate understanding, the representation of the knowledge space has been simplified in figure 2.8, and K0, the knowledge space at the start of the design, has been identified. Repeatedly, the architect reviews their sketches to find new ideas; for example, in the first sketch, they see a Chinese motif that appears stable due to intertwining lines. The architect chooses to work with this motif throughout the sequence and retains this attribute. In the second sketch, they test motif alternatives by introducing curved lines. Curved lines are brought from knowledge K to propose a partition of the initial concept (disjunction). However, they are not pleased with the aesthetics of the result, realizing that glass integration will be technically difficult with curved edges. That observation is then integrated as new knowledge into K (conjunction). They then produce several drawings, and observing the third sketch, they see a linear form that leads them to consider the use of cables. Again, they choose to test this new attribute from K, as seen in the fourth drawing. However, with this sketch, they realize that the cables do not allow for complete glass integration across the entire surface of the library; thus, they abandon the idea of cables.

This dynamic illustrates the essence of design according to the CK theory: a constant back-and-forth between generating possibilities in C and expanding knowledge in K. This interaction is crucial, as it allows for transforming indeterminate concepts into concrete, testable solutions, thereby enriching the designer's knowledge space in the process.

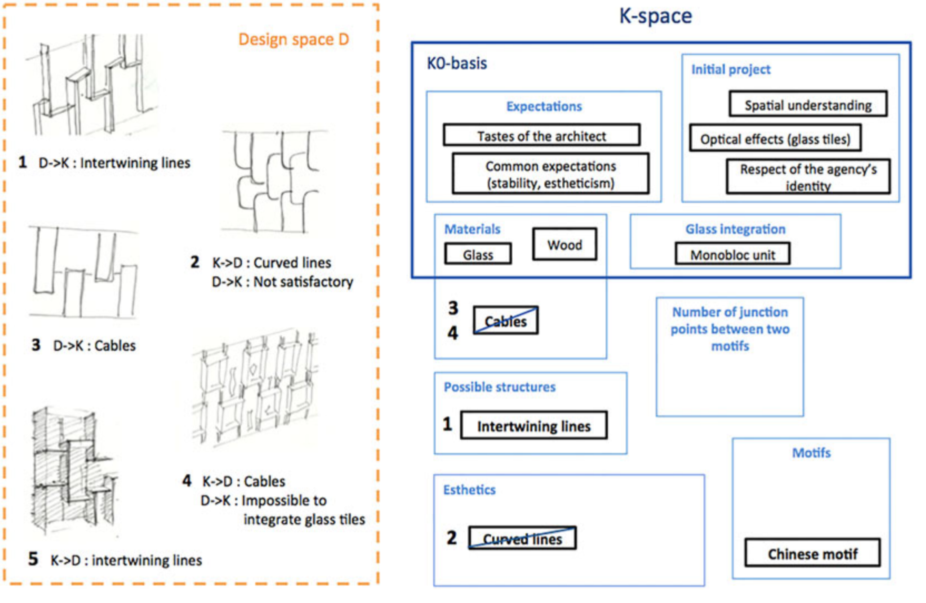


Figure 2.8: *Illustration of the dynamic between the Concept (C) and Knowledge (K) spaces, showing how ideas evolve and interact between these two spaces during the design process (Brun et al., 2016).*

Information in CK

As highlighted by Hatchuel et al. (2013), the K space is intrinsically linked to accessible knowledge, and therefore, it is relative to the architect's ability to identify and mobilize this knowledge. In the previous chapter, knowledge is defined as the result of the integration of information. Access to knowledge is not enough; it may be necessary to seek additional information, and through the knowledge process, transform this information into knowledge. The CK model allows highlighting this phenomenon (see Figure 2.9)

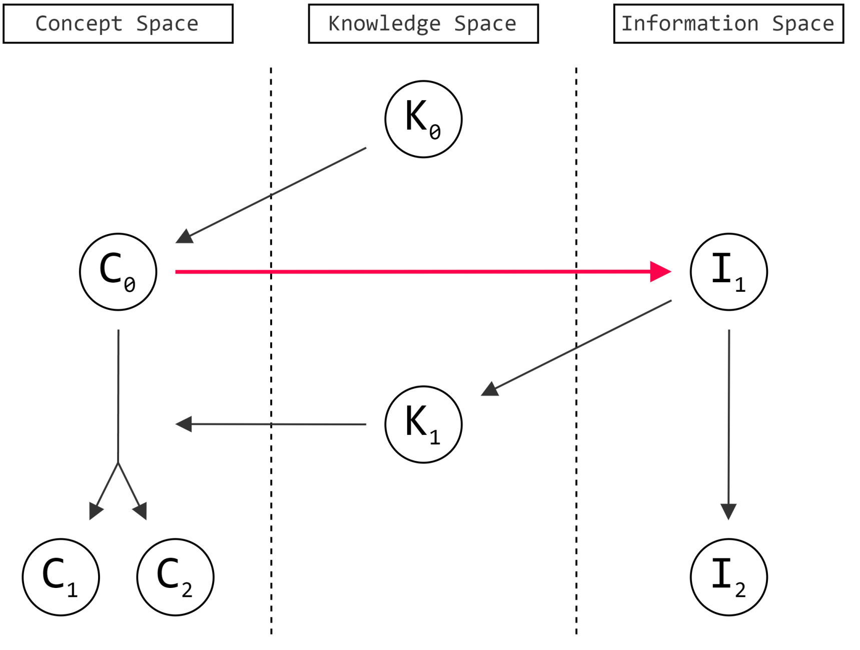
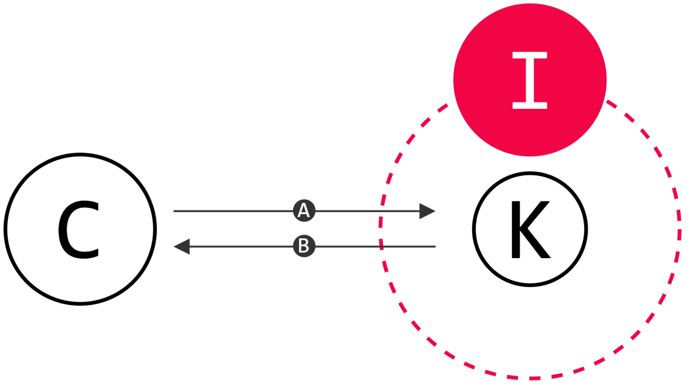


Figure 2.9: *Evolution of the CK model to integrate the notion of information, demonstrating how information is integrated to become usable knowledge in the design process.*

This conceptualization emphasizes the importance of search methods and information use. Indeed, merely exploiting existing concepts will not be enough to create new knowledge; it is necessary to seek new information to both feed the concept and extend the knowledge space. Thus, the proposal to augment the Concept-Knowledge (CK) model by considering information into a Concept-Information (CI) model. This enhanced model aims at encapsulating integration processes and provide a more comprehensive approach to information search (see Figure 2.10).



Ⓐ Search for attributes, verification in I and knowledge expansion through **conjunction**

Ⓑ New attributes implementation, concept creation and **disjunction** into alternatives

Figure 2.10: *Integration of the information status in the CK model to lay the foundations of the conceptual model.*

Recent advancements highlight that CK theory not only synthesizes existing theoretical frameworks but also serves as a versatile foundation for the development of innovative theories and models. It has inspired the creation and extension of various conceptual approaches, leading to diverse applications in both theoretical and practical domains (Hatchuel et al., 2018; Kazakçi, 2009; Salustri, 2014). This versatility is further evidenced by its application across numerous support tools and contexts. Despite its broad applicability, there remains a noticeable scarcity of CK theory-related publications in the architectural domain, resulting in a lack of empirical data and theoretical developments tailored to this field. In particular, CK theory does not explicitly address the intricacies regarding expansion in each dimension space C⇒C and K⇒K. Regarding the expension of concept space, the Function-Behaviour-Structure (FBS) model is employed. The FBS model delineates the design process into distinct issues, providing a more detailed insight into the cognitive processes involved in design. The expansion of K will be addressed in regards to information in the next section.

2.3.2.2 Function Behavior Structure model

Gero and Kannengiesser (2004) contend that their models differ from most others in "explicitly" representing the steps of reformulating the design and/or problem as new information is generated. Gero and Kannengeiser (2014) write that FBS offer conceptual tools for understanding designing and provide bases for design activity to be studied independently of domain. Furthermore, similarities with the generation of knowledge can be found in Gero's Function-Behavior-Structure (FBS) (Dorst & Vermaas, 2005; Gero, 1990; Hatchuel et al., 2018).

The FBS ontology is based on the idea that every concept can be represented in terms of *function*, which describes what the concept is intended for, *behavior*, which describes what the concept accomplishes, and *structure*, which describes the concept itself (Gero & Kannengiesser, 2014). In his original model, Gero (1990) defines 6 design issues: requirements, function, expected behavior, structural behavior, structure, and documentation. The *function* (F) describes the designer's intentions, the *expected behavior* (Be) corresponds to what is expected from the *structure* (S), and the *structural behavior* (Bs) is the actual behavior of the implemented structure. *Requirements* (R) and *documentation* (D) are external issues that initiate and conclude the design exercise.

To move from one issue or ideation state to another, Gero describes 8 cognitive processes (see Figure 2.11): (1) problem *formulation*, in which the required functions are transformed into behaviors that the design solution must exhibit; (2) the *synthesis* of a structure aimed at achieving the targeted behaviors (to fulfill the formulated expectations); (3) the *analysis* of the structure to define its actual behavior; (4) the *evaluation* of the behavior against the previously defined expectations; and (5) the *documentation*, which is the externalization of the structure intended to be transferred to the next actor involved in the overall architectural project process. Finally, Gero's model proposes three *reformulation* processes R1 (6), R2 (7), and R3 (8), all three considered as vectors of generativity (Kan & Gero, 2008) as they introduce new attributes.

In understanding the design process, reformulation (R1, R2, R3) plays a crucial role. R1 concerns the reformulation of the structure within a defined design landscape. Therefore, R1 carries the risk of remaining limited to a constrained conceptual landscape and can be translated into an exploration through a given set of parameters (Erhan et al., 2017). According to Erhan et al. (2017) there is a risk of getting stuck into that process due to the possible number of possibilities. R2, on the other hand, involves a reconsideration of expectations, thus expanding the problem space, and can lead to new occurrences of R1. Finally, R3 represents a fundamental questioning of the problem formulation (H. Jiang et al., 2014), which can also lead to reformulations R1 and R2. R2 and R3 relate to the aforementioned co-evolution theory as they represent how a solution affects

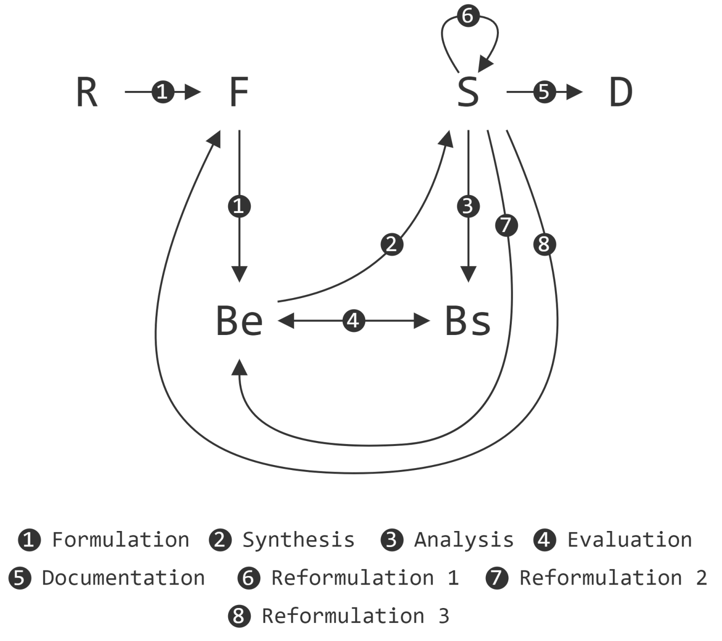


Figure 2.11: *The Function Behavior Structure Model based on Gero & Kannengiesser (2014).*

the redefinition of the problem (C. Alexander, 2002; Dorst & Cross, 2001). Eventually reformulation lead to the expansion of knowledge.

Ultimately, the FBS ontology brings more precision to the conceptual model. The C component is further modified into D (Design) to emphasize the integration of the FBS ontology, which alone does not explicitly address the issue of knowledge and information developed in CK. Thus, the FBS model aids in examining the various reformulation processes of structure, expectations, and problems, and their potential impacts within architectural design (see Figure 2.12). This perspective aims to enrich comprehension of how designers access the necessary information to fuel these reformulation processes.

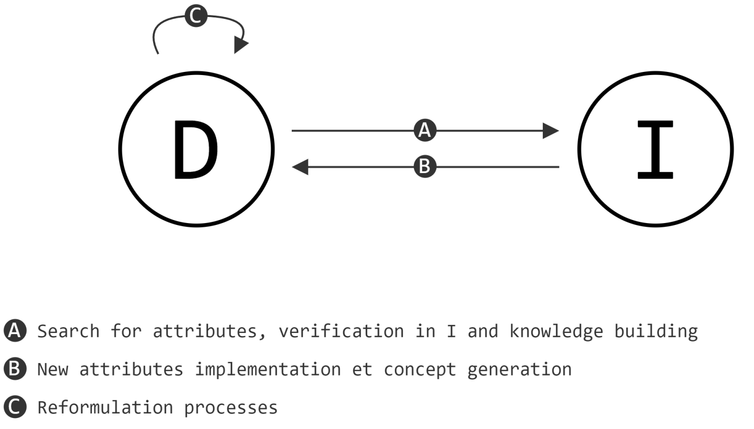


Figure 2.12: *Integration of FBS and representation of reformulation processes*

Information in FBS

In the design process, the concept of structure (S) emerges as a critical element. Within the framework of CK theory, structure represents the tangible outcome of the expansion of the concept space (C), which in turn stimulates the generation of new knowledge through conjunction. Moreover structure is where reformulation happens. In this context, the role of information is pivotal it can be responsible for reformulation therefore act on the structure itself. In CK theory, this involves the reintroduction of knowledge back into the concept space, leading to further partition (new alternatives) and expansion of the concept space. Similarly, in FBS, information is processed into knowledge, which is then reintegrated into the existing structure for reformulation. This new knowledge acts as a catalyst for information search, underpinning the process of reformulation (see Figure 2.13). The structure, therefore, is not just an outcome but also a critical point of intervention where reformulation occurs.

The impact of the reformulation process is related to the level at which it occurs (R1, R2 or R3). In both CK and FBS models, the degree to which information contributes to reformulating the design structure determines the extent of its influence on the overall design process. This relationship highlights the interplay between information, knowledge, and structure in design, underscoring the importance of information search in shaping the design outcomes.

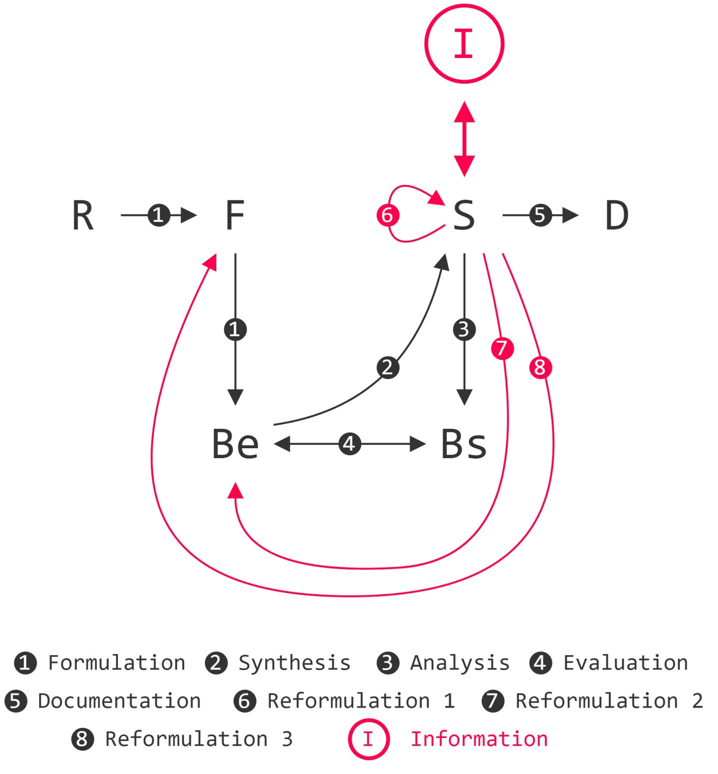


Figure 2.13: *Integration of information into the structure within the FBS model as a catalyst for reformulation.*

With the process of expansion within the conceptual space (C) now outlined, the focus shifts to the expansion within the knowledge domain and, by extension, the role of information.

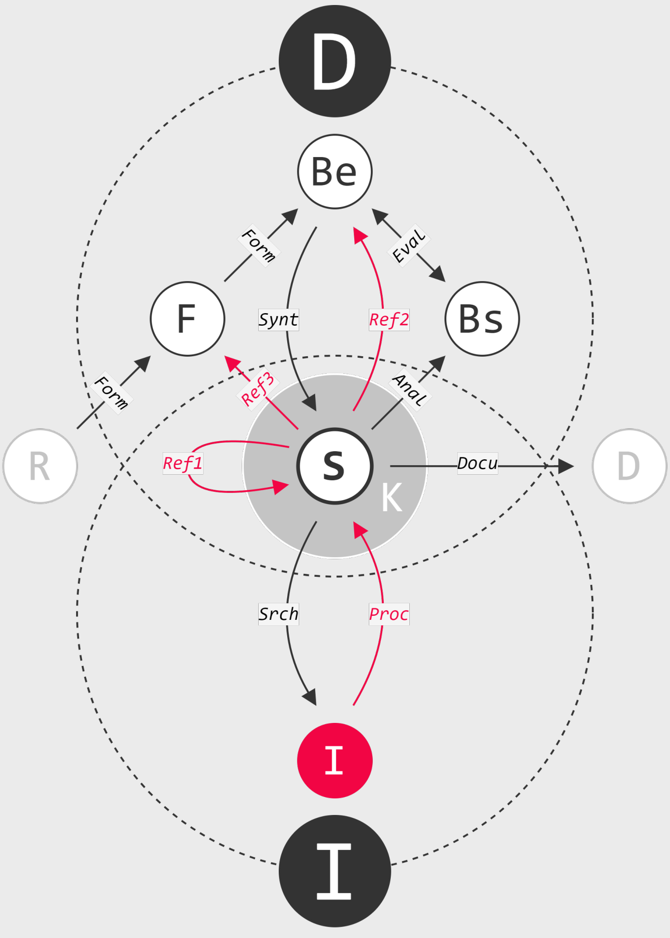
2.3.3 Summary

This section delves into the complexities and dynamics of design theory, a field marked by its multifaceted nature and ongoing debates concerning its logic, foundations, and contemporary relevance. Central to these discussions is the nature of design problems, which are often described as ill-defined due to their incomplete, inconsistent, or vague specifications. These characteristics necessitate approaches that can adeptly handle the unpredictability and expansiveness inherent in design solutions.

The discussion delves into the concept of generativity in design which offers a distinct perspective from traditional decision theory and creativity. Generativity is about the capacity to conceptualize and create new alternatives using known building blocks in fundamentally novel ways. The section then transitions to explore various models of design, focusing on how they categorize and understand the design process. Two theoretical models stand out in this context for their relevance to information search in design: the CK (Concept-Knowledge) model and the FBS (Function Behavior Structure) model.

The CK model is notable for its explicit treatment of the mobilization of knowledge (and indirectly information) in design. It represents a departure from other models that do not address this topic as directly. On the other hand, the FBS model is distinguished by its representation of the design process in distinct issues, offering a clear structure for understanding the transformation of information status throughout the process. These two models provide complementary insights, playing a crucial role in deepening the comprehension of information search challenges within design, particularly during initial phases. As the scope broadens to include not only ideation but also the entire design process, grasping the concept of generativity becomes essential. The implications of information retrieval in relation to these models are then considered.

Integration of FBS as the design process



*Requirements **R** are formulated into a function **F**, from which the expected behavior **Be** is derived. A structure **S** is then synthesized based on Be. This initial structure is grounded in prior knowledge **K**, forming the basis for further analysis of the actual structure behavior **Bs** and evaluation. The structure also serves as a foundation for reformulation, facilitating the expansion of the initial structure and, consequently, the broadening of knowledge. This process positions the structure as the central element from which knowledge, and by extension, information **I**, can be integrated for disjunction and subsequent reformulation. The model includes three levels of reformulation. Reformulation 1 impacts only the structure itself. Reformulation 2 influences the formulation of Be, adjusting how the function's performance should manifest. Reformulation 3 modifies the initial function F. Each level of reformulation not only refines the design but also expands the underlying knowledge base, enabling a progressive integration of new information and insights into the structure. Documentation signals the end of a design episode or the step beyond which there is no further reformulation.*

2.4 Information as Inspiration

Information search in design can be understood as an inspiration process, encompassing any information that might be integrated in the design solution. This process is nuanced as it can oscillate between inspiration and fixation. Inspiration, as defined by Goncalves et al. (2016), is the process by which a stimulus (a triggering information element), once perceived and integrated, nourishes the interpretation of the design problem as well as the development of potential solutions. Therefore inspiration can be qualified as information that appeared stimulating and that has been integrated into the design as knowledge (see Figure 2.14) to induce reformulation. Even technical information, which at first glance may seem uninspiring, can hold significant reformulation potential. For example, a fire safety standard could stimulate new design approaches. In essence, the inspiration process described here adresses the expansion of knowledge through information (K⇒K).

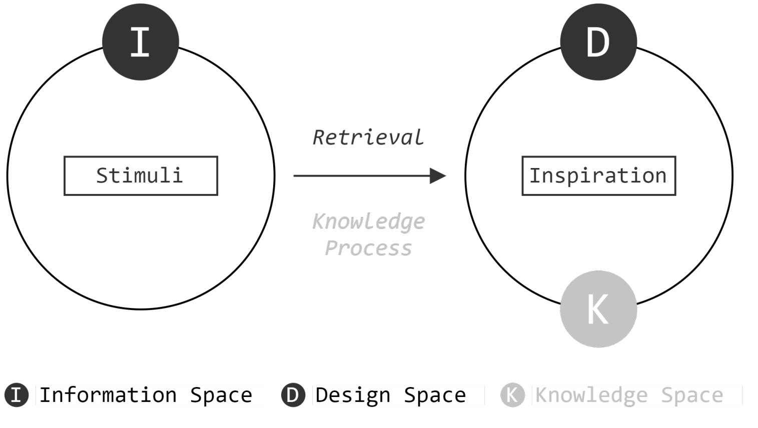


Figure 2.14: *Stimuli to inspiration as a knowledge process in design activity.*

Goncalves et al. (2016) looked at how novice designers in engaging in ill-defined problems are challenged with many ambiguous moments such as finding how to start (particularly with novice designers) and how they approach search for inspiration. They delved into the inspiration search process in design, employing Eckert and Stacey's (2003) approach with a focus the stimulus rather than the source. They delineated the process into three phases: the definition of search inputs, the search for stimuli, and the selection of stimuli (see Figure 2.15). This structured approach to finding inspiration is aimed at either redefining the design problem, seeking solutions for a sub-problem, or refining an existing sub-solution. Therefore, each cycle of this process can lead to a reformulation process as seen before but also the reformulation of the search task itself, aligning with the Search as Learning (SAL) concept. However, it's important to note that this inspiration process can be unconscious, with designers often unaware of how their search for inspiration directly influences their design outcomes. This framework, and its exploration within the context of architecture, design theory, and the digital era, lays the groundwork for understanding how information retrieval plays a crucial role in the design process. The 3 stages of inspiration will be looked at and discussed in regards to that context then implemented accordingly as part of the design process in the conceptual model.

2.4.1 Definition of search inputs

Keywords play a pivotal role in the information retrieval process. While Goncalves et al. (2016) emphasize explicit keyword definition in their experiment, they acknowledge that keyword formulation typically occurs implicitly in the design process. This distinction is crucial as it impacts how designers approach and engage with information retrieval systems (search engines in this case).

Identifying appropriate keywords or constructing queries in general can be challenging (Rieh et al., 2016; Xie & Cool, 2009). Common issues include a tendency towards satisficing behavior when ideal information is not found, reluctance to invest significant effort, and overestimation of search skills. It's referred to as the critical role of both prior knowledge and digital literacy in this process of keyword formulation (Dosso et al., 2020). Prior knowledge aids in focusing on relevant information and crafting more precise queries (Aula, 2003; Dommes et al., 2011; Sanchiz et al., 2017). Furthermore queries can initially be synthesized using selected words from the task description and later build more refined queries using more precise terms for better results. Therefore the query itself can be subject to reformulation processes (Wildemuth et al., 2018). However, learners still acquiring knowledge face a dual challenge: not only do they struggle with formulating effective search queries due to limited subject knowledge, but they also can find it difficult to accurately interpret the information they retrieve. This is also referred to as the sense-making paradox (Butcher & Sumner, 2011). This further underscores the importance of conceptual knowledge in create tasks as it would serve as prior knowledge for building queries.

Regarding the important semantic aspect of search tasks, other factors can have an impact on the search task and eventually the design process. The influence of design task constraints on keyword use is one significant aspect. The level of constrainedness in a design task affects the proportion of task-specific words used in search queries (Biskjaer et al., 2020). This can lead to a “combinatorial

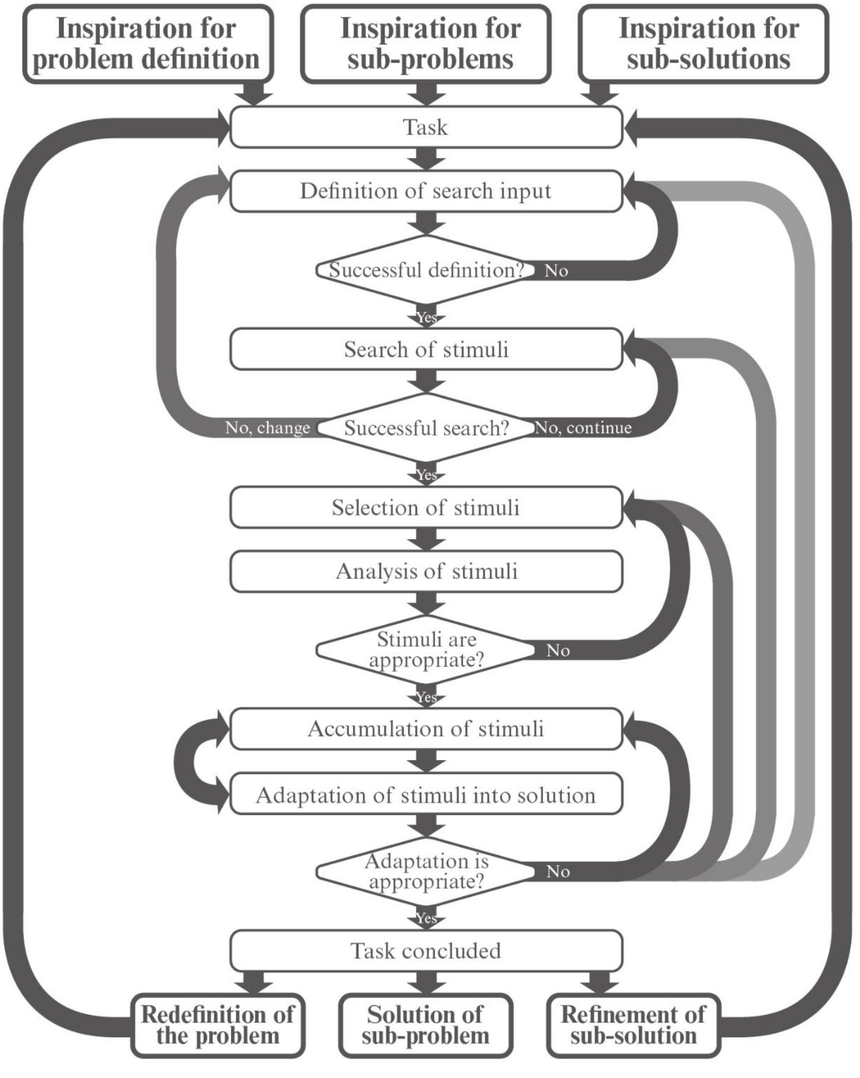


Figure 2.15: *Visualization of the inspirational search processes that could be observed at different moments of the design process (visualization adapted from Eckert and Stacey, 2003) (Goncalves et al., 2013)*

explosion" of possibilities, especially in tasks with high constrainedness (Perkins, 1994). Contrary to the assumption that tighter constraints might narrow the scope of inspiration, Biskjaer et al.'s (2020) research suggests that a more extensive array of available keywords fosters flexible and varied search behaviors, although it may result in an overly broad range of outcomes.

One other aspect of keyword definition is highlighted in image search (Cho et al., 2022). The importance of semantic integrity in retrieval systems indicates that users are primarily interested in the semantic content inferred from images (Enser et al., 2007). This leads to the challenge of "aboutness" which refers to the difficulty in ensuring search results align closely with the intended topic (Huang & Kelly, 2013). This challenge underscores the intricate relationship between a user's prior knowledge and their digital literacy skills. In the realm of image search, the ability to formulate effective queries that accurately capture the desired semantic content hinges on the user's understanding of the subject matter and adeptness with the search tool, thus reinforcing the need for a blend of knowledge and digital proficiency.

Digital literacy plays an important role in information search. It encompasses not just proficiency with search tools but also essential cognitive abilities in search tasks like planning, evaluating, and processing information (Sharit et al., 2015). This can be related to specific metacognitive knowledge, where designers not only use search tools effectively but also reflect on and adapt their strategies, enhancing their awareness and control over their thought processes. This metacognitive knowledge is crucial for efficiently navigating, filtering, and utilizing information, thereby improving the quality and relevance of search outcomes in the design process.

The idea of inspiration as a trigger for reformulation in design is intertwined with the design process itself. The FBS ontology suggests that reformulation only occurs in response to an existing structure. The structure is either derived internally from the design development however if designers are only starting the project, the structure can be made specifically for inspiration search. Novice designers, as observed by Goncalves et al. (2013), often don't know where to start, demonstrating a structured approach to keyword formulation at the beginning of the design process based on the task constraints or even keywords (see Figure 2.16). This initial challenge is often mitigated by the designers themselves as they become more adept at articulating the problem or defining the expected behavior, thus refining their search inputs

While this discussion has primarily focused on semantic prompts, it's important to acknowledge the broader spectrum of modalities in search inputs. First depending on the source. Goncalves et al. (2016) mainly examine digital retrieval systems, but the insights regarding search inputs extend beyond search

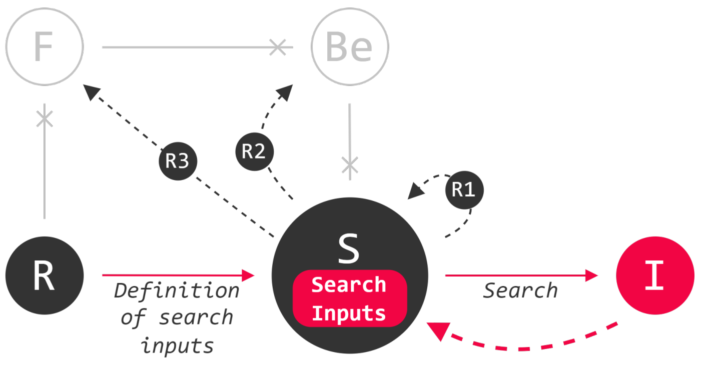


Figure 2.16: *Structure as the definition of search input based on the requirement keywords and the definition of the problem is thus based on the informationr retrieved or the query itself is reformulated.*

engines. Henderson (1991) demonstrated that sketches, as opposed to CAD software, enhance information retrieval among colleagues, highlighting the impact of modality on the effectiveness of information searches. Additionally, people are often preferred as information sources for complex tasks due to their ability to accommodate a wider range of modalities (voice, gesture, sketches,. . .) (Byström, 2002). In a more recent study Lee (2024) has studied how digital ecosystems have impacted the multimodal aspect of information retrieval among people in architecture. This empirical data is still relevant as advances in technology allow now such multimodal interaction with digital search systems, however research in this area is still scarce (Kwon et al., 2021).

2.4.2 Search of stimuli

Goncalves et al. (2016) identify five distinct typologies of search: active search with purpose and without purpose, passive search, random active search and passive attention. *Active search* with a specific objective is a targeted endeavor, where the individual deliberately seeks out certain stimuli with a clear goal in mind. This could involve browsing the Internet for specific information, consulting a book, or engaging in social interactions to pose a question (Eckert & Stacey, 2003). This type of search requires searchers to have a clear understanding of their objectives, which in turn hinges on their prior knowledge. In contrast, active search without a specific objective, also known as continuous exploration, lacks a defined intention to solve a particular problem. This approach is more about broadening or refreshing one's understanding of a subject. It is a common practice among designers to stay abreast of crucial topics in their field (Wilson, 1997). Here too, prior knowledge plays a role in guiding the exploration.

Passive search and *passive attention* represent more incidental forms of information acquisition. Passive search involves the accidental discovery of relevant stimuli that are then incorporated into the design process, often described as serendipity or unexpected discovery (Keller et al., 2006; Suwa et al., 2000). In this scenario, the individual is not actively seeking information, yet remains cognitively alert to potentially relevant stimuli that could indirectly relate to an ongoing problem (Ware, 2008). Passive attention, meanwhile, occurs when stimuli are perceived without active integration into a specific problem context, such as while watching TV or during casual conversations. In these instances, there's no immediate intent to solve a problem, nor a conscious acknowledgment of the potential impact of a stimulus (Wilson, 1997). However, it's noteworthy that these states of attention can rapidly transition into more active searches for stimuli, illustrating the fluid nature of these search typologies, which can evolve according to the situation.

Goncalves et al. (2016) delve deeper into the subtleties of these search strategies, highlighting particularly intriguing behaviors like passive but intentional search. This strategy involves using a search engine deliberately to create opportunities for serendipity, namely finding useful information without actively looking for it. Consequently, the authors describe an alternative strategy: *random active search*. This appears when the designer seeks to determine their own objectives and similarly relies on a search engine, raising the question of the search system influence but also how the sensemaking paradox discussed earlier plays a role in that decision.

Search engines are increasingly seen as tools for provoking opportunistic encounters with stimuli. Seifert et al. (1995) note that search engines can be utilized to stumble upon relevant information in an unstructured manner. This observation aligns with the findings of Mougenot et al. (2008) and Herring et al. (2009), who suggest that the Internet can serve as a brainstorming tool, helping designers to identify keywords they initially hadn't considered. Such behavior could stem from the uncertainty inherent in not knowing what to search for, echoing the sensemaking paradox. Without a specific direction, designers might rely on chance to find relevant stimuli, highlighting the inherent unpredictability in the process of defining search inputs.

Figure 2.17 proposes a new version of the conceptual model integrating the identified information search strategies

However in Goncalves et al.'s study (2016), the students were interviewed post-activity, thus providing retrospective accounts of their search types. It can not be excluded that an initially active search results into a passive encounter,

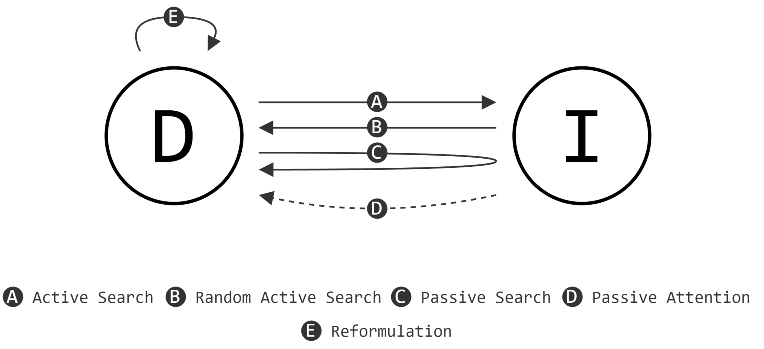


Figure 2.17: *Integration of research strategies observed during design activity (Goncalves et al.2016).*

especially considering limited knowledge and therefore lack of semantic richness in the input definition. A query that lacks semantic richness can start as an active search with purpose yet, given the poverty of the prompt, it can return a wide variety of results improving the chances for serendipity (Huang & Kelly, 2013; Sedghi et al., 2011). Consequently, this blurs the distinction between active and passive searches, suggesting that these strategies might not be as distinct as initially presumed. Serendipity, unexpected by nature, can nevertheless be facilitated through deliberate search efforts. Given this, the role of contemporary search systems becomes crucial in shaping the strategies employed to encounter those unforeseen discoveries. A dynamic revision would involve examining the triggers in information retrieval against the actual information retrieved. The following representation simplifies the complexities to better understand the interplay between these 2 factors (see Figure 2.18). It illustrates the concept that inspiration may not align with the initial search definition by distinguishing two key movements: from design to information (the search process) and from information back to design (the retrieval of inspiration).

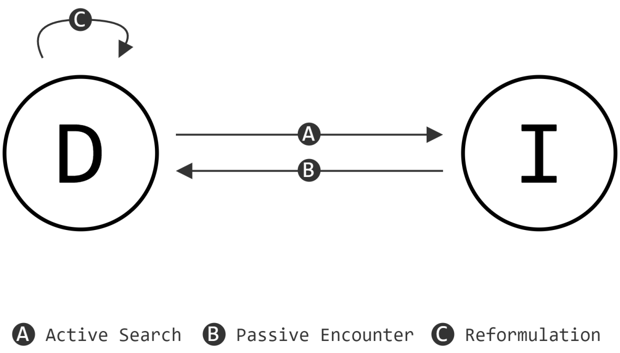


Figure 2.18: *Search strategies decomposed as simple actions based on query emission and inspirational response.*

2.4.3 Selection of stimuli

Inspiration is used as a broad term for the information processed to serve design. However, the motivations behind selecting specific sources of inspiration can be diverse. Goncalves et al. (2016) identify five key drivers for the search for inspiration: relevance, reliability, recognition, verification, and curiosity. While all these drivers play a role in the design process, they might have different implications in regards to reformulation.

Relevance involves selecting stimuli based on their perceived appropriateness to the design problem at hand, drawing focus to familiar stimuli (Hicks et al., 2002; Kwasitsu, 2003). *Reliability* dictates the choice based on the perceived credibility of the stimulus, favoring information that appears formal or factually grounded. *Recognition*, on the other hand, is about selecting stimuli that are already known or familiar to the participants. Selections based on recognition often do not lead to idea generation. Furthermore, in contrast with relevance as they are independent of the problem's context, recognition can occur even if a stimulus is considered irrelevant. *Verification* acts as a driver where an information element either validates or invalidates a project attribute. Finally, *Curiosity* drives the selection of stimuli that are unfamiliar, eye-catching, or unexpected, contrasting with the more confirmatory nature of relevance, verification, and recognition (Gonçalves et al., 2016). This diversity in drivers underscores the multifaceted nature of inspiration in the design process, with each driver contributing uniquely to the selection of stimuli. Concerning curiosity, Goncalves et al. (2016) found the information associated effort to be a selection criterion. Curiosity often drives designers to explore various types of stimuli, including the use of analogies, which play a significant role in the architectural design process.

Leclercq et al.'s (2002) study on analogy in architectural design reveal a nuanced picture of how analogies are employed throughout the design process in architecture. These analogies are drawn from both information coming from personal knowledge and external sources, with no clear preference for either, underscoring a dynamic interplay between familiarity and novel information. This frequent use of analogies, often occurring spontaneously without explicit rationale, as ingrained cognitive strategy. The almost constant reliance on analogy suggests that while curiosity through analogy is common, its association with low-effort information might indicate a potential for bias.

In regards to effort, Purcell et al. (Purcell et al., 1993) categorize information as either "restrictive" or "expensive." Restrictive information, rooted in prior knowledge, tends to constrain exploration and is linked to the first four drivers (relevance, reliability, recognition, verification). Conversely, the information is considered expensive as it would require the knowledge process effort of integrating the new information as a new attribute into the design. However the latter is a driver for design as unexpected stimuli would be integrated diverging from the initial design brief (Shah et al., 2001). Therefore, the higher effort of perceiving, transferring and transforming distantly related stimuli into the context of the brief might lead designers to overlook them (Ozkan & Dogan, 2013).

This resonates with previous statements regarding the type of knowledge and therefore information. When discussing the preferred type of knowledge in create search tasks in IIR, Urgo et al. (2020) have shown procedural knowledge to be favored compared to conceptual knowledge seen as conveying more effort when addressing an ill-defined problem. Similar results have occurred in design studies. Examining the types of information critical to design reveals a preference for procedural information (Y. Zhang et al., 2020). This preference suggests that the driver for selecting information based on curiosity might be influenced by the type of the knowledge sought, and possibly also by the source and modality of that information. As observed, people are often preferred sources, additionally, the modality of information, such as texts, might not be as popular as visual content, further influencing the selection process based on the type of knowledge and the way it is presented or accessed.

Goncalves et al. (2016) also highlight the role of provocative stimuli, external inputs that facilitate a shift in reference and encourage divergent thinking. This helps designers break free from prior-knowledge based responses (Bono, 2007; Grossman & Wiseman, 1993; Shah et al., 2001). This phenomenon also resonates with reformulation. More globally provocative stimuli can very much be the result of carrying a lesser associated effort. Nonetheless, it's important to note that neither provocative stimuli nor other forms of stimuli consistently result in appropriate inspiration (Gonçalves et al., 2016). In cases where they do not, it can even lead to fixation.

Contrasting with inspiration, fixation is characterized by an uncritical reuse of existing attributes, often without evaluating their relevance (Cardoso & Badke-Schaub, 2011; Jansson & Smith, 1991; Purcell & Gero, 1998) (see Figure 2.19). However, as pointed out by Cardoso and Badke-Schaub (2011), the boundary between inspiration and fixation is theoretical as they point out that the boundary between inspiration and fixation is not always clear. This nuance can be explained via the concept of analogical distance.

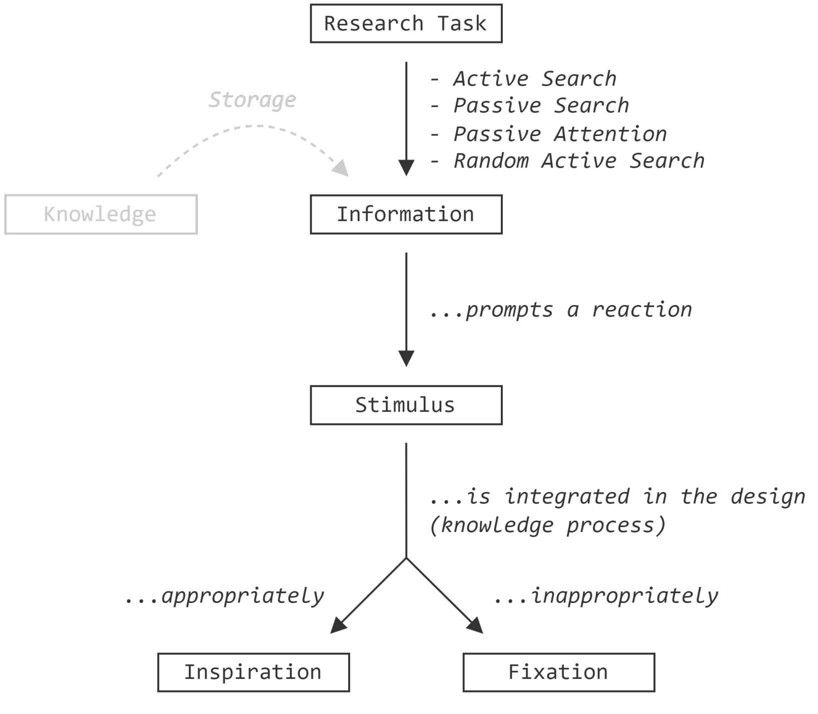


Figure 2.19: *Information status in design based on Cardoso and Badke-Shaud (2011).*

2.4.4 Fixation effect and analogical distance

The analogical distance plays a crucial role in design. This distance represents the conceptual gap between the source information (stimulus) and the problem context (target). It can be either close, belonging to the same domain and thus supposedly requiring less effort to integrate, or distant, thereby hopefully fostering creativity up to the point of encouraging cross-disciplinary boundaries (Ozkan & Dogan, 2013).

Commonly, resorting to analogically close sources is a frequent tendency, often explained by the principle of the "path of least resistance" (Ward, 1994). This approach can lead to the uncritical adoption of existing solutions, potentially failing to adequately address the specific problem encountered hence fixation. Fixation however does not pertains to information but also to prior knowledge when designers carry over unhelpful design attributes from a previous example (Cardoso & Badke-Schaub, 2011). Exploring distant sources, although more demanding, can open up unexpected avenues for design exploration. For example, drawing inspiration from an artistic domain to solve a technical problem illustrates the application of a distant analogical distance.

However, Goncalves et al. (2016) point out that distant related stimuli even though considered drivers for creativity are not always beneficial for design or do not always translate into relevant attributes (Chan et al., 2015). Similarly, Venkataraman et al.(2018) showed that far-field analogies increase novelty but decrease quality. Timing for stimuli during the design process is also debated (Kim & Maher, 2023).

Crilly (2015) notes that certain environments may actually encourage fixation. This phenomenon typically arises in environments where ideas are personally owned and closely associated with their originators. Consequently, individuals may become protective of their concepts and resistant to alternative approaches, which can lead to fixation. In architectural offices for example, top decision-makers might prefer to develop projects in a consistent manner to attract and maintain a client base. This dynamic is not limited to individual cases but can extend to organizational strategies. For these firms, maintaining a consistent design approach can be crucial for attracting clients, turning fixation into a form of consistency and even a trademark characteristic of the firm, thus becoming a key selling point.

Crilly (2015) identifies other fixation factors, including prior knowledge, which, as previously discussed, can limit further exploration due to reliance on existing information. Initial ideas also play a role, potentially constraining subsequent exploration. Constraints, including those related to project requirements or operational limitations, can significantly shape the definition of search inputs. Lastly, the briefing, representing external factors such as the client expectations and indirectly the project requirements (as defined in the FBS framework), can also encourage fixation indirectly by delineating the scope of what is considered acceptable or desirable in the design outcome.

Analogical distance addresses creativity but not directly generativity (Dahl & Moreau, 2002; Ward, 1994). Indeed it is concerned with ideation but does not address the subsequent perceived effort into producing a relevant entity as a support for further development (Le Masson et al., 2011). Regarding the latter, a distant stimulus could very well be selected based seemingly on curiosity, but actually influenced by the lesser perceived effort for generativity.

Furthermore, quantifying analogical distance remains a challenge. It is influenced by multiple factors, including the subjective nature of information perception and interpretation (Chan et al., 2015). Information search strategies play a crucial role: the way individuals search for, find, and select information, as well as the tools they use to do so, will largely determine the analogical proximity of their stimuli. However regardless of subjectivity regarding inspiration or fixation, it seems awareness for "potential fixation" and eventually digital literacy could greatly benefit architects in their search effort.

Ultimately, the impact of the search tool on fixation is an essential consideration in the design process. The tools that designers use to search for information significantly influence their search strategies. Notably, when designers lack prior knowledge or are in pursuit of serendipitous discoveries, they often depend on the recommendations offered by the search system. This reliance on search tools can shape the direction of their inquiry, potentially leading to fixation if the tools do not support diverse and relevant recommendations. Thus, the design and functionality of search tools play a crucial role in either facilitating a broad exploration of ideas or inadvertently contributing to fixation by limiting the scope of information encountered.

2.4.5 Summary

Information search in design is a nuanced process that often serves as a quest for inspiration. Inspiration is the process of integrating information into the design, and thus transforming it into knowledge. Inspiration can emerge from any source, even seemingly uninspiring technical data.

The process of searching for inspiration involves various strategies. This process is largely unconscious, meaning designers are often unaware of how their search for inspiration impacts their design. It can be broken down into phases: defining keywords, searching for stimuli, and selecting stimuli.

Keyword definition is pivotal in the information retrieval process. While it often occurs implicitly in the design process, its explicit formulation can significantly impact how designers engage with information retrieval systems. The choice of keywords can be influenced by the designer's prior knowledge, digital literacy, and the specific constraints of the design task.

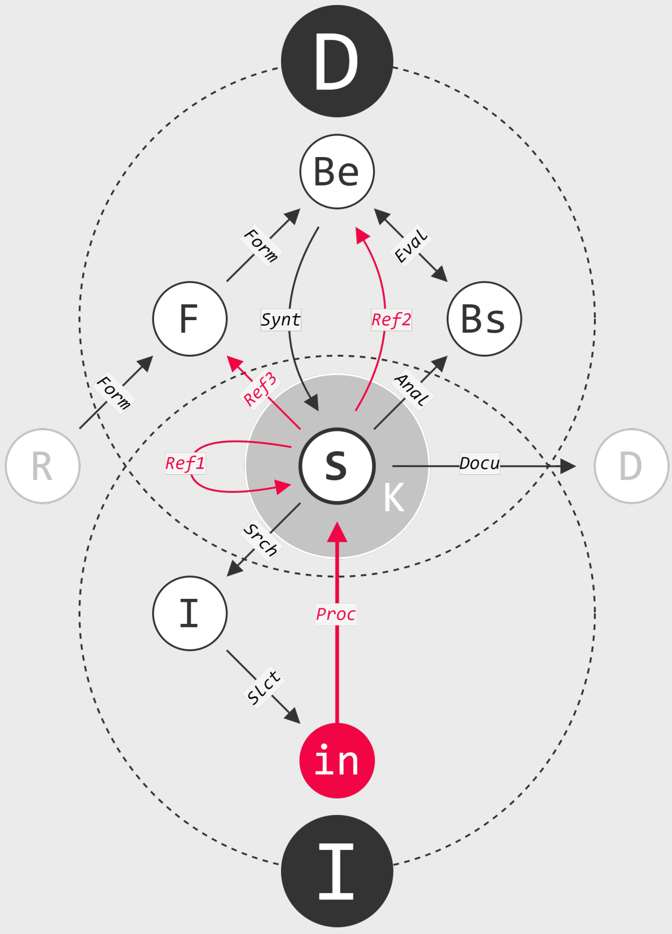
The search for stimuli is categorized into various typologies: active search with a purpose, passive search, random active search, passive attention, and active search without purpose. Each type of search reflects different levels of intention and prior knowledge. However, strategies can be the result of a dynamic process and a search task that started as an active search can lead to passive encounters.

The selection of stimuli involves various drivers: relevance, reliability, recognition, verification, and curiosity. These drivers influence the design process differently. For example, relevance focuses on the appropriateness of stimuli to the design problem, while curiosity drives the selection of unfamiliar or unexpected stimuli. The effort associated with processing these stimuli also plays a role in their selection and can eventually lead to fixation.

In contrast to inspiration, fixation in design refers to the uncritical reuse of existing attributes. However, distinguishing between inspiration and fixation is not straightforward. The concept of analogical distance proposes to elucidate those subtleties. Analogical distance refers to the conceptual gap between the source of inspiration and the context of the problem at hand. Close analogies, which often stem from prior knowledge bias, typically result in the recycling of existing solutions and can lead to fixation. On the other hand, distant analogies encourage greater generativity by reducing the likelihood of deterministic outcomes, although they do not always guarantee beneficial design results.

Finally, the role of search tools in influencing search strategies and potentially leading to fixation is noteworthy. The recommendations from these tools play a critical role in determining the analogical proximity of the stimuli. Awareness of potential fixation and the development of digital literacy are therefore crucial for architects in their search efforts.

Integration of inspiration as the process of information retrieval



*Inspiration manifests as a three-step process: defining search inputs, searching for stimuli, and selecting appropriate responses. The structure **S** serves as the foundational base from which the search query is derived, essentially defining the search inputs. Information **I** represents the pool of external knowledge navigated through various search strategies. Eventually, selected stimuli are chosen to be integrated into the structure. The information that successfully integrates and thus undergoes the knowledge process is called inspiration **in**.*

2.5 Information Retrieval Systems

Architects' focus on visual stimuli is integral in their practice of sketching self-generated ideas, a skill developpped during their education. Research by sketching has proven to be essential in the architectural process (Bilda et al., 2006; Goldschmidt & Smolkov, 2006; Ozkan & Dogan, 2013; Purcell & Gero, 1998; Suwa & Tversky, 1997). Visual sources in architecture, such as photographs and plans, underscore the importance of visual stimuli in architectural design (Campbell, 2017). Research by Blandino et al. (2023) indicates that visual stimuli significantly enhance designers' creative performance. In contrast, textual stimuli, while contributing to the variety and quality of ideas, seem less influential in the architectural field. A decline in the number of ideas generated is observed when textual information is used, possibly due to the higher effort required for their comprehension (Gonçalves et al., 2016; Moreno et al., 2014; Royo et al., 2021). Even in combined stimuli (textual and visual) such as architecture case studies, Akin (2002) noted that architects usually used them for evaluating their own ideas rather than as direct inspiration, due to the unstructured and implicit nature of information from these cases however they require a lot of effort and eventually cause fixation (Chan et al., 2011). Videos, another visual stimulus combined with audio, are not frequently mentioned in the context of architecture, however they are seen as having an influential role in design activities (Loke et al., 2017). This evolving information landscape in architecture indicates a dynamic interplay between visual stimuli and Internet resources, reshaping traditional information-seeking behaviors and highlighting the unique ways architects engage with and process information.

Designers, and particularly architects, are increasingly inclined to use the Internet as a primary source of information. Bystrom's research (Byström, 2002) reveals that with complex tasks, there's a trend towards utilizing diverse information types, favoring human over documentary sources. This reflects a shift from traditional reliance on printed materials to a more dynamic engagement with various online resources. Campbell's findings (Campbell, 2017) further support this trend, showing that architecture faculties in the US, while valuing printed resources, predominantly favor online sources for information seeking. Interestingly, despite the fact that her results support the use of people as information sources she finds that librarians are often underutilized.

2.5.1 Recommender systems

Search engines, frequently used in daily tasks, play a crucial role in design, particularly through information search. However, as Zhang et al. (Y. Zhang et al., 2020) have pointed out, they may not be suitable for specific tasks such as searching for inspiration or ideation. The risk is that they often favor 'appropriate' responses, thereby amplifying the fixation effect.

Research in recommender systems has attracted interest over the years (L. Jiang et al., 2019; Pla Karidi et al., 2018; Yang et al., 2020). In the field of technology enhanced learning, recommender systems have been studied for over 10 years (Beel et al., 2013). Recommender systems are generally acting to predict users' choices based on past behavior. In education they are considered software systems used to recommend learners about learning resource, process choices, and information filtering due to information overload (Melville & Sindhwani, 2010). The goal is to maximize learner's performance. With the passing times, recommender systems are going through evolution; more and more features are added to fit the user's needs. In relation to creativity, Afridi et al. (Afridi et al., 2020) have looked at the potential of recommender systems in learning situation and found recommender systems to be powerful tools for serendipity in research given the adequate user interface. However the role of academic supervision is very important to facilitate serendipity and recommendations, in autonomous scenarios, the architects would be relating on popular search system and their underlying recommender system.

Recommender systems have been instrumentalized towards other objectives than learning. Areas such as e-commerce and streaming platforms already exploit these systems to offer personalized suggestions (L. Jiang et al., 2019). They either help navigate the high quantity of products based on collaborative filtering or even suggest products based on past preferences. Furthermore, it raises the question of information as the product itself. There is a high risk there will be an incentive for effortless information. One example are videos: 70% of watch time on Youtube is due to suggested content by its recommender system (Tollon, 2021). Tollon (2021) argues that those technologies come to solicit certain kinds of actions from users, making such actions more or less likely, and in this way influencing the kinds of things one comes to value. For example, videos are more likely to convey procedural knowledge (Li et al., 2022).

Finally there is the issue of known as the search engine bias. As recommender systems are based on information's metadata results might reveal a statistical bias that may eventually influence users perceptions about a topic (Noble, 2018). It can be intentional such as information manipulation (Epstein & Robertson, 2015) or unintentional when popular beliefs are carried on as information that has been proven to be false yet the statistical weight carries on as misinformation. More nuanced in architecture the association between an architect and a specific building or a tool with a specific style...

The challenge intensifies when architects or designers have limited prior expertise. In such scenarios, the search for inspiration or learning materials becomes particularly challenging (Butcher & Sumner, 2011). The search results, often shaped by the statistical inferences of recommendation algorithms, may lead to a constrained design space. This issue becomes more critical under time constraints, as initial solutions explored tend to disproportionately influence the final design decisions (Jansson & Smith, 1991), especially with visual stimuli (Gonçalves et al., 2013; Masaya et al., 2023). Considering generativity, the synthesis aspect becomes crucial. While the focus on inspiration is often design-oriented, technical information is also essential for structural synthesis. This raises questions about how tool-related information impacts the design process.

The conceptual model has progressed from focusing on knowledge to its expansion through information, leading to the formation of the CI model. This model further evolved into DI, integrating the dynamics of reformulation from the FBS model. The model now incorporates the recommendation process typical of search engines (see Figure 2.20). This additional loop on "I" represents the interconnectedness of information through algorithms, which are often not transparent to the user. This inclusion emphasizes the influence of recommendations on design and underscores the complexity of the current information landscape.

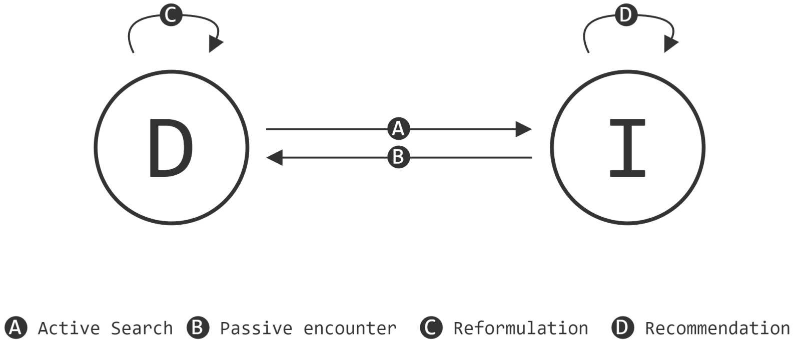


Figure 2.20: *Integration of recommender systems in the conceptual model.*

2.5.2 A note on Artificial Intelligence

The integration of artificial intelligence (AI) in the field of information search in architectural design presents a significant evolution, opening new perspectives. AI systems, particularly natural language processing models, enhance information acquisition by deeply analyzing data to identify correlations and patterns not always perceptible with traditional search methods (Chaillou, 2022). This ability to uncover hidden insights offers considerable potential to stimulate the design process.

However, this integration is not without challenges. The risk of statistical biases inherent in the training data of AI models poses a major issue. These biases can subtly influence search results, directing designers towards more conventional solutions, thus risking the perpetuation of a broader creative fixation problem (Hofer, 2004; Ståhl et al., 2021). Moreover, the complexity of the underlying mechanisms of AI models often remains a mystery to end-users, which can lead to overconfidence or misplaced trust in AI-generated suggestions.

Zhou and Park (2023) challenge the traditional text prompt by implementing a multimodal approach to search query. They investigate multimodal approach by using both text and sketches as prompt material using AI-augmented applications alleviating the issue of semantic knowledge enforcing a less oriented research or differently oriented. While empirical results remain limited, there is an emerging potential for these developments to transform into tools that assist in concept generation.

In architecture and in design, AI's integration into design has transformed the ideation process by enabling users to externalize their ideas directly to the system, bypassing the need for traditional synthesis. For instance, when a designer prompts an AI with a concept like "a Ferrari that looks like a UFO," the AI can generate the corresponding structure. These AI-generated outputs serve as initial structures that designers can further iterate upon. This capability of AI to act as a generative tool, materializing abstract ideas into workable structures, significantly broadens the scope of what designers can conceptualize and create. Currently, AI can produce outputs ranging from textual descriptions to images and even music. There is also emerging potential for AI to generate more complex structures like 3D models. However, this advancement brings with it the risk of biases, similar to those found in specific recommender systems and search engines, potentially leading to a fixation effect. Such biases in AI-generated content can subtly guide designers towards conventional solutions, thus presenting both a remarkable opportunity and a challenge in leveraging AI for creative design.

Furthermore, the advent of AI has introduced the concept of latent space within the architectural realm (Chaillou, 2022). In information retrieval, the latent space functions as a representation of textual data. For example, when analyzing architectural designs, AI can process descriptions and characteristics of various buildings and represent these as points in a multidimensional space. Buildings with similar styles or functions are closer together in this space, facilitating more intuitive similarity matching. These techniques, similarity matching, clustering, and classification, capture underlying semantic structures within data, potentially revealing relationships between architectural typologies and their features. As a result, this approach enhances information retrieval and supports various downstream tasks. However, it is crucial to recognize the inherent risk of bias in the data that populates the latent space. Such biases can limit the scope of design exploration, reinforcing conventional ideas and potentially hindering generativity by prioritizing familiar or subjectively favorable attributes over novel design solutions.

Understanding how designers access and integrate information is essential to effectively support the design process. The focus of this examination has largely been on information search methods and their influence on design, especially during the ideation phase. Nonetheless, it is recognized that the concept of generativity reaches beyond just ideation. It includes not just the generation of ideas but also the ability to create corresponding entities (Le Masson et al., 2011).

Let's consider generative text AI, such as ChatGPT. This technology simplifies information retrieval, functioning similarly to a search engine. Users can request information or even direct the AI to compose entire texts. The resulting structure, whether produced by the user or the AI, can be further reformulated. The quality and bias of the AI's response are influenced by the precision of the initial prompt, highlighting the importance of user input in guiding the AI's output.

The closer example to architecture pertains to image generation. Visual materials such as renders can be crucial in architectural design documentation. Traditionally, rendering such images would require significant effort as a synthesis and documentation process. However, tools like MidJourney or DALL-E simplify this task by generating images based on prompts, thereby bypassing the conventional effort-intensive processes. Moreover, these tools streamline image creation, meaning the prompt itself must act as the complete structural guide reformulated by the AI without additional input. Conversely, the new structure can very well serve as a reformulation trigger for further developments. This approach is highly solution-oriented, yet the images generated offer limited practical information, necessitating further consideration by the architects who need to consider all practical and technical underlying aspects of the overall project.

Advancements in AI have also led to the development of plan generators and 3D model generators that not only provide visual representations but also incorporate detailed information such as circulation materials and technical specifications. Conversely, this information can serve as a robust source of inspiration, akin to traditional texts, images, or technical drafts sourced through search engines or colleagues. These developments prompt a critical evaluation of the role of architects in the design process and the potential narrowing of their tasks to adjusting queries in the near future. This situation raises fundamental questions about where architects and designers add the most value and how design education should evolve in response to these technological advancements.

As AI increasingly influences architectural design, emphasizing digital literacy becomes crucial. Strategies to manage biases and foster a conscious, critical engagement with AI technologies are essential, enhancing users' awareness of both the capabilities and limitations of AI. Successfully integrating AI into the architectural design process requires not only discernment and critical reflection but also a robust understanding of digital tools and systems. The framework proposed in this research aims to provide a comprehensive basis for evaluating AI's impact on design, strongly focusing on digital literacy. While AI will undoubtedly play a significant role in the future of design, currently, architects still bear the primary responsibility for synthesizing their own structures and documentation. The next section will explore how current tools, including AI, can influence information search and, consequently, the entire design process.

2.5.3 Summary

Studies have indicated that visual stimuli are more popular than textual stimuli. Textual information, while diversifying and improving the quality of ideas, appears less influential in architecture, possibly due to the higher effort required for comprehension. Furthermore, videos, which combine visual and audio stimuli, are not commonly mentioned in architecture but are more recently recognized as influential in design activities. The evolving landscape of information in architecture suggests a dynamic interplay between visual stimuli and Internet resources, reshaping traditional information-seeking behaviors.

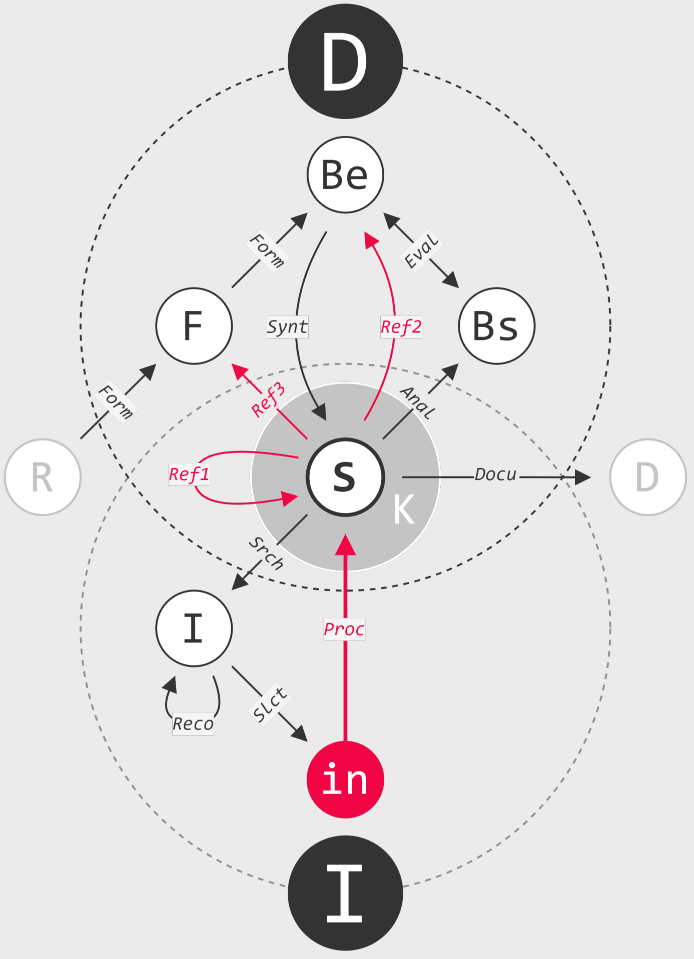
The Internet has become a primary information source for architects. Research reveals a trend towards utilizing diverse information types in complex tasks. This trend is supported by findings that architecture faculty prefer online sources for information seeking, despite acknowledging the value of printed resources.

Recommender systems, typically used in search engines, play a significant role in design. These systems predict users' choices based on past behavior. However, in the context of architecture, there's a risk that such systems might favor "appropriate" responses, amplifying the fixation effect. The challenge is more pronounced for architects with limited expertise, as search results shaped by recommendation algorithms may lead to constrained design spaces.

The integration of AI in information search presents new opportunities and challenges. AI systems, can analyze data to identify patterns and correlations, stimulating design potential. However, statistical biases present in recommender systems can be transposed to AI models, directing designers towards fixation. The complexity of recommendation mechanisms often remains opaque to end-users, which can lead to misplaced trust in AI-generated suggestions.

AI's role in architecture has transformed the ideation process by enabling externalization of ideas to the system, with minimum effort into synthesis. AI-generated outputs serve as initial structures for further iteration by designers. However, biases in AI-generated content can guide designers towards conventional solutions.

Emphasizing digital literacy is essential in addressing the challenges posed by recommender systems and eventually AI in architectural design. The examination has primarily focused on information search methods and their impact on design, particularly during the ideation phase. However, the concept of generativity extends beyond ideation to include the creation of corresponding entities. While AI will play a significant role in this aspect of design in the future, architects currently bear the primary responsibility for synthesizing their own structures and documentation. The next section will explore how current tool influence information search and the entire design process.



Recommendation functions as a dynamic reformulation process within the level of information I, steered by the search system itself. This process significantly influences search strategies, to the extent that the definition of search inputs is often kept abstract to fully leverage the benefits of recommendations. By directing the flow of information retrieval, recommendations help refine and guide the search process, allowing users to explore broader or more nuanced possibilities without committing to specific initial parameters.

2.6 Tools in architecture and discontinuity

This section delves into the emergence of visual stimuli within the architectural design process. Stimuli can originate from information searches but traditionally they are generated by the architects themselves. A critical, yet unexamined aspect is how these two sources of stimuli interplay and influence the design process. Understanding how externally sourced visual stimuli from searches interact with internally generated ideas by architects could shed light on the dynamics of inspiration. Analyzing this relationship could offer deeper insights into the cognitive processes of design, the role of information, and the ways in which architects navigate the vast landscape of inspiration to articulate their architecture through their visual tools.

Representation tools play a pivotal role in architectural design, acting as the conduit through which the abstract concept of a design is transformed into a tangible reality in accordance with generativity. The evolution of these tools from traditional drawing boards to sophisticated digital environments marks a significant shift in how architects conceptualize and materialize their ideas. This progression and its diverse effects on the design process have been thoroughly explored in the literature (Carpo, 2003; Carpo, 2017; Ching, 1991; Picon, 2010).

While traditional tools are often perceived as direct extensions of the architect's thought process, digital tools are primarily regarded as aids for documentation or production. This distinction suggests that digital tools may not contribute as intimately to the design process as their traditional counterparts. However, this perspective may overlook the significant evolution and ongoing advancements of these digital tools. As these tools develop, they offer new possibilities for integration into the design process, challenging the historical view and potentially transforming their role from mere documentation aids to integral components of the design process. The essence of this evolution reflects a broader discussion on the integration of technology in design practices, highlighting how these tools influence the architect's workflow, creativity, and ultimately, the final architectural product.

2.6.1 Drawing, Sketching and Drafting

Leon Battista Alberti's (1997) conception of an architect's role, focusing on design over construction, elevated drawing as a fundamental aspect of architecture. It serves as a medium for expressing architectural ideas and as a link between thought, design, and construction (Scheer, 2014). However, the role of drawing has been contentious, perceived both as a communication tool for construction and a medium for reflective action. Drawings, in the context of generativity, synthesize ideas and invite new insights when perceived, thus enabling architects to directly understand the interplay between an idea and its visible representation (Scheer, 2014).

In his book "The Thinking Hand," Juhani Pallasmaa (2009) distinguishes between sketching and drafting. He describes sketching as an immediate, spontaneous drawing form, crucial for exploring and communicating ideas. Sketching facilitates visual thinking and problem-solving, and is integral in collaborative design efforts. Conversely drafting involves precise representation of objects and spaces in plans, sections, and elevations. Pallasmaa does not specifically use the term "drafting" to refer to this activity. Instead, he refers to it as a form of drawing that is concerned with the precise representation of objects and spaces in two-dimensional plans, sections, elevations, and specifications for construction. He emphasizes the importance of this type of drawing as a means to translate the architect's ideas into a form that can be understood and realized by others, such as clients, contractors, and builders. Pallasmaa stresses that both sketching and drafting are important in the architectural design process, each contributing uniquely to the development and refinement of ideas.

The design process in architecture can be conceptualized as a series of discretization processes (Claeys, 2023). Architects intentionally create discontinuities, both in the imagery they produce and across different stages of the design process, as a means to better comprehend and interpret reality (Scheer, 2014). This discretization represents the approximation of an idea into a form that emerges through the tools used in its representation. As such, the tools' capacity to discretize, or break down complex ideas into manageable, interpretable parts, fundamentally shapes the final architectural product. Each step from an initial sketch to detailed construction drawings involves a series of approximations that introduce certain discontinuities. These discontinuities are dictated by the representation capabilities of the tools employed, marking transitions that punctuate the design process. Given that architects predominantly think in terms of representation, considerable research has been devoted to understanding the impact of various representational tools and the outputs created by these tools on the architectural design process (Carpo, 2003; Carpo, 2017; Ching, 1991; Picon, 2010).

Within the context of the conceptual model, the representation is associated with changes in knowledge (Brun et al., 2016). A sketch for instance is seen as a structure (S) created by the architect, forming a basis for further development through iterative reformulation. In contrast, drafting is more closely linked to the process of documentation. However, according to Pallasmaa (2009), drafting also contributes to the design process, suggesting that drafting, while predominantly a documentation tool, can also function as a form of sketching.

This observation blurs the distinction between synthesis and documentation (see Figure 2.21). While sketching allows for greater flexibility and potential for reformulation, documentation processes, typically through drafting, are less flexible and therefore less prone to reformulation, as making changes at this stage would require considerable effort. It is understandable to consider that in the more advanced stages of the design process, reformulating the objectives of the design could necessitate extensive reworking of the project. This aligns with Macleamy's curve, which illustrates the diminishing flexibility and rising costs as a project progresses and emphasizes the importance of early stages (Paulson, 1976). The documentation process should therefore be considered as a series of structures that evolve in time through iterative discretization processes that are prone to discontinuities through reformulation.

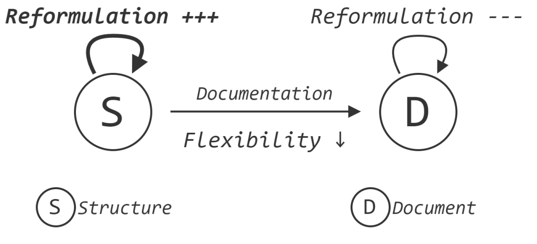


Figure 2.21: *Documentation is illustrated as a spectrum of flexibility for reformulation, which varies significantly across different stages of the design process. At the structural level (S), flexibility is relatively high, making it more amenable to reformulation. In contrast, at the document level (D), the process becomes far less flexible. This delineation underscores a gradual transition from a highly dynamic to a more static state within the documentation process, reflecting a decrease in the potential for modifications as the project moves closer to the final document.*

This also suggests that the ambiguity between synthesis and documentation is exacerbated when architects use the same tools for both purposes, which may diminish the perception of discontinuity. When using tools such as pen and paper, which are often perceived as creating a more direct and intuitive connection between the designer's mind and the physical act of drawing, the architect perceives a continuous flow of thought, reinforcing the illusion of a seamless transition between synthesis and documentation (Pallasmaa, 2009, 2012; Schön, 1983). The uniformity of the physical tool, whether for sketching or drafting, fosters a perception of the design process as continuous.

However, the increasing integration of digital tools into the design process, or even their complete replacement of traditional analog sketching methods, can disrupt this perceived continuity (Safin et al., 2014). The digital environment introduces different types of interactions and can create a distinct separation between the ideation and documentation phases. This shift often emphasizes the seamless flow that was more typically experienced with analog methods. Conversely, newer digital tools have been designed to mitigate these issues, aiming to restore the flexible nature of evolving structures and to seamlessly integrate various phases of the design process.

2.6.2 Digital culture and complexity

Considering the rich heritage of architectural practice, the blurring of lines between sketching and drafting has led to the sacralization of analog drawing as the essential design tool (Claeys, 2023). Concurrently, the rise of digital tools, originally conceived to replicate the look and feel of traditional sketching, has seen a shift towards being predominantly used for documentation (Elsen et al., 2010). This shift raises pertinent questions about the implications of discontinuities that occur when separate tools are employed for design and documentation or when digital tools made to emulate analog drawing are used for synthesis within the design process (Goldschmidt, 1991; Safin et al., 2014). These considerations are crucial for understanding the evolving nature of architectural design processes and the potential discontinuities they introduce.

The longstanding debate between analog and digital drawing in architecture and design centers around the intuitive connection offered by analog methods versus the precision and efficiency of digital tools. Proponents of analog drawing argue that the tactile experience of using pencil or pen on paper fosters greater creativity and exploration (Claeys, 2023; Pallasmaa, 2009). Conversely, Kolarevic (2003) advances that digital tools like CAD software provide precision and facilitate collaboration, proving invaluable in complex projects. Adding to the digital toolkit, new hybrid solution such as VR, AR or even graphic tablets have been particularly notable for bringing the tactile feel and immediacy of sketching into the digital realm, offering nuanced experiences. However, those opinions are largely debated. Ultimately, the choice between analog and digital methods depends on the designer's individual preferences and project needs, with many incorporating both to harness their respective strengths (Elsen et al., 2010; Pallasmaa, 2009; Schön, 1983).

Digital tools have induced a paradigm shift in design, moving away from traditional post-modern design terminologies to embrace new concepts like continuous versus discrete and material versus space (Oxman, 2008). The complexity and range of these tools have expanded exponentially, raising questions about the necessary expertise for architects. In this context, digital tools could significantly influence discontinuity in the design process.

Claeys (2023) highlights complexity as a factor contributing to discontinuity. He uses the perspectives of Simon, Berthoz, and Dehaene, and delves into the complex cognitive landscape that architects navigate. Simon's (1956) concept of bounded reality underscores the difficulties faced by architects, who must filter and process an overwhelming amount of environmental information. This limitation necessitates the reliance on procedural rationality, where architects develop routines, potentially influenced by their tools, to manage decision-making effectively. Berthoz's notion of "simplexity" (2012) further illuminates this complexity, blending simplicity with complexity to describe how architects adapt to challenging environments. Finally, Dehaene's analogy of architects as statisticians (2012) adds another layer, depicting them as professionals who construct probable realities based on prior experiences. All those can be referred to as prior knowledge based fixation as result of tool related effort. The discontinuity is driven by the tool or more precisely, the knowledge of the tool. This simplification can sometimes lead to predefined paths dictated by software routines, thus limiting exploration. It is therefore crucial for architects to understand these tools and remain critical of the cognitive biases they might introduce.

The complexity of digital tools like in the case of search engines recommender systems, come with biases. These biases, rooted in programming logics and user interfaces, discreetly influence design choices. As Serriano (2003) points out, computer applications materialize in their graphical interface and internal logic assumptions about the construction of objects and the representation of space. The accessibility of functions, for example, directly influences their frequency of use. Software, tailored to the specific needs of certain communities, transpose prevalent practices from the analog world into the digital universe, leading to modeling results oriented by the choice of application itself, thus constraining the exploratory space of architects (Serriano, 2003). Additionally, if the design process is approached as solution-oriented, with the solution manifesting through representation, it implies that the nature of the solution is influenced by the representational tool employed.

This raises a question regarding situations where prior knowledge is lacking or absent and synthesis becomes a challenge. Architects could either decide to reformulate either the design problem or solution in order to align with tool expertise or try to fill the gaps by learning new functionalities or even switch to other tools. In case of the latter they may find the information they're looking for, information that is close enough, or even come across entirely different information and use it as inspiration. This could result in reformulation aimed at mitigating the tool's lack of knowledge as seen in the inspiration process, however here, information retrieval is concerned with the tool rather than design itself.

The search for relevant information emerges as a way for architects to break free from the complexity of these tools. By exploring various references, precedents, and case studies, architects can expand their horizons, increase their generative potential, and challenge established routines. However, this search can paradoxically reinforce biases and fixation risks if not approached with critical awareness. The conceptual model proposes to consider this dynamic in understanding the interaction between design and information search for tool-knowledge expansion (see Figure 2.22).

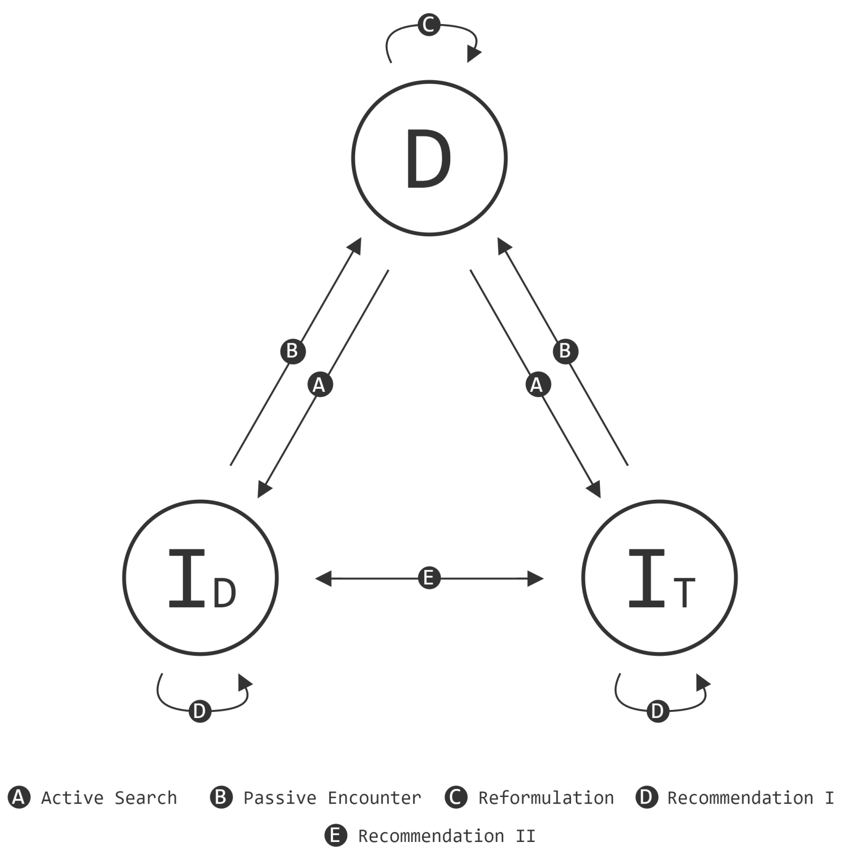


Figure 2.22: *Separation of information into design-related information (ID) and tool-related information (IT) on the other hand.*

Parametric design environments (PDEs) are a prime example of complexity. As described by Oxman (2006), PDEs represent an evolution in digital tools, introducing new design thinking logics integral to the design process rather than serving as documentation aids. However because of their inherent complexity they are also particularly sensitive to prior knowledge based fixation (Yu, 2014). Despite the ubiquity of information retrieval in today's digital landscape, its role in navigating PDEs remains underexplored. This gap suggests a potential for leveraging information retrieval to mitigate the challenges presented by a lack of prior knowledge in design contexts. By examining the influence of PDEs on architectural practice, this discussion aims to shed light on both the challenges and opportunities presented by complex digital tools, especially in relation to addressing gaps in information retrieval and fostering inspiration within the design process.

2.6.3 Parametric Design

Parametric design stands as a notable illustration of the evolution in digital tools and the accompanying shift in thought processes within architecture. Its growing prevalence across both academic research and professional practice marks a significant departure from traditional design methodologies, and leads to the development of complex tools (Davis, 2014). Despite its widespread adoption, the intricacies of parametric design's application in architecture remain an ongoing debate, especially regarding the extent to which architects fully comprehend the potential of parametric design to enhance and support their creative intentions (Sanguinetti & Kraus, 2011).

Parametric design in architecture is a process based on defined parameters that allow automation, exploration, and management of data. In parametric design, the design process translates into the development of an algorithm, consisting of assembling a series of functions into a procedure determining the structure's behavior. Thus, the algorithm becomes a formula through which design ideas are transformed into dynamic structures, enabling exploration and adaptability to various project requirements. The Parametric Design Environment (PDE) is a term used by Yu (Yu et al., 2012) to describe the digital software environment that allows the designer to create and manipulate parametric models (see Figure 2.23).

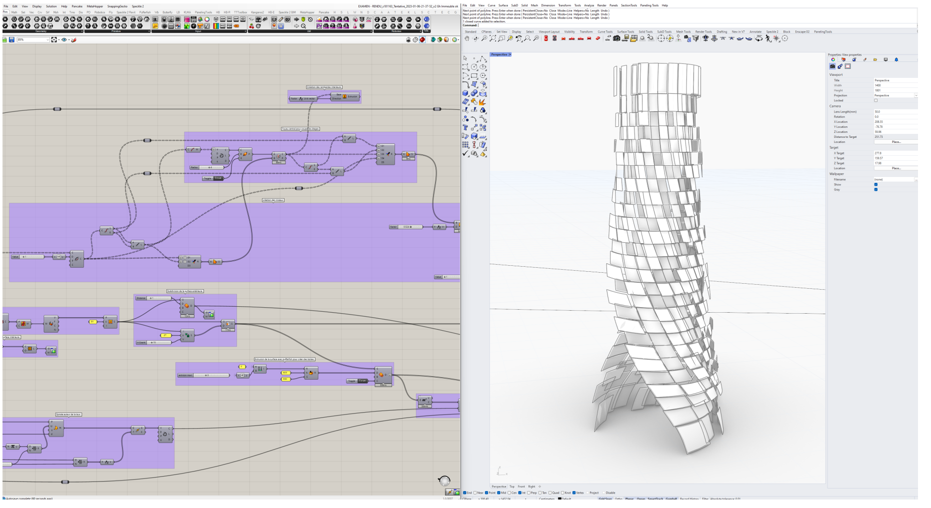


Figure 2.23: *Example of a PDE called Grasshopper© within Rhino3D©. The algorithm on the left (visual script) generates the geometry or architecture on the right.*

Thus Parametric design mediates between two worlds: an abstract, coded system from which complex spatial forms emerge through rule-based mathematical expressions, and the space where architects apply their design knowledge to address the needs of people, cultures, communities, and cities (Sakamoto & Ferré, 2008). Architects must assess variations, design data flow routes, and adjust parameter values and revise rules to create building forms. In a typical parametric design process, Yu et al. (2012) distinguishes between two levels: the design knowledge level and the rule algorithm level. Architects apply specialist knowledge in the former and indirectly apply it through defining rules and their logical relationships in the latter, also known as parameterization. This logic was built on top of the FBS ontology as a superscript (see figure 2.24)

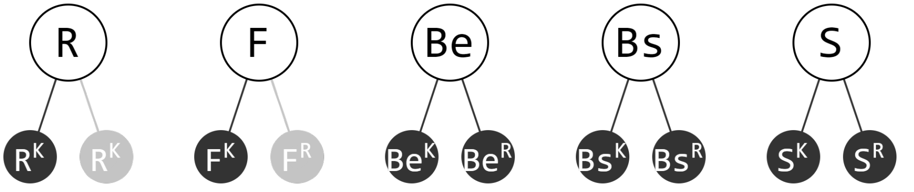


Figure 2.24: *Yu et al. (2012) base for building the FBS superscript*

Rule algorithm refers to the set of rules or instructions that define how a design solution can be generated or evaluated. These rules can be explicit or implicit and may include technical, aesthetic, or functional considerations. In the context of PDEs, rule algorithms are typically represented as a series of parameters and equations that define the relationships between different design variables. Design knowledge, on the other hand, refers to the designer's intuition, creativity, and ability to make aesthetic and subjective judgments. This type of knowledge is often tacit and cannot be easily formalized or codified. It is what distinguishes human designers from algorithms and machines. A detailed description for each sub-category can be seen in Yu's (2014) coding scheme (see table 2.4)

One of the main advantages of PDEs, according to Yu (2014), is their ability to support exploration and experimentation in the design process. By offering a flexible and responsive platform to designers, PDEs allow architects to easily test and modify a significant number of options until finding a satisfying solution. However, Yu also points out disadvantages that underscore a dual complexity: inherent complexities of the tool itself and the complexities arising from adopting a new mode of thinking (rule algorithm level).

Transitioning from analog representation to a parametric model presents a significant challenge. It requires architects to translate their thought processes into algorithms. Woodbury (2010) emphasizes that this shift necessitates a unique skill: "parametric thinking." Moreover parametric thinking and design thinking are seen as distincts in addressing design problems, a dual process that PDEs try to alleviate by allowing fluid transitions between them (N. Kelly & Gero, 2021).

Table 2.4: *Description of FBS design issues with Rule-Knowledge attributes*

Design Issues	Description
R^k	Review of the design brief. So no rule algorithm are involved
F^k	"The concept of function does not vary between different design environments". This is important to consider when studying design tools. Function variable defines the teleology of the object meaning what is is for. Yu et al. (Yu et al., 2014) argue that design tools do not affect the function F of the design. In PDEs the architect still needs to consider design intentions and decide what factors to parameterize or constrain and where to assign the weight for specific factors (Ottchen, 2009). However, it could be argued that, to a certain degree, the tool itself may be considered an integral component of the architect's expertise.
$Be^{r,k}$	speculate the effect of the later proposed structure or set up algorithm or think about algorithms to achieve their goals
$Bs^{r,k}$	The "actual behavior" Bs-k is the evaluation of output geometry and Bs-r evaluates the structure of the rule algorithm
$S^{r,k}$	S-k is what it is and S-r is what it is in terms of the algorithm (what the algorithm is)

Regarding the tool, Yu highlights the risk of "premature compromise." This occurs when designers solidify design decisions too early, subsequently limiting their exploratory scope. This tendency to rely on familiar routines suggests a fixation induced by the tool. This observation aligns with previous highlighted research on challenges arising from the complexity of PDEs (Abdelsalam, 2009; Aish & Hanna, 2017; Davis et al., 2011; Woodbury, 2010).

Visual programming and easy recipes

Visual programming (VP) tools, like Grasshopper©, have become prevalent in parametric design due to the unpopularity of textual programming in architecture (Leitão et al., 2012). VP is compelling because it allows for the description of complex forms through sequences of components and their relationships. Once the algorithm is established, exploration within predefined parameters leads to various design outcomes. The use of algorithms in VP means that the resulting structure can be accessed without the need for in-depth understanding or interpretation, akin to following a recipe (see Figure 2.25). Parameterization permits different outcomes and design adaptations, although limited by the initial design space set by the algorithm. While this simplifies the design process, it also risks increasing fixation within the constraints of the predefined parameters.

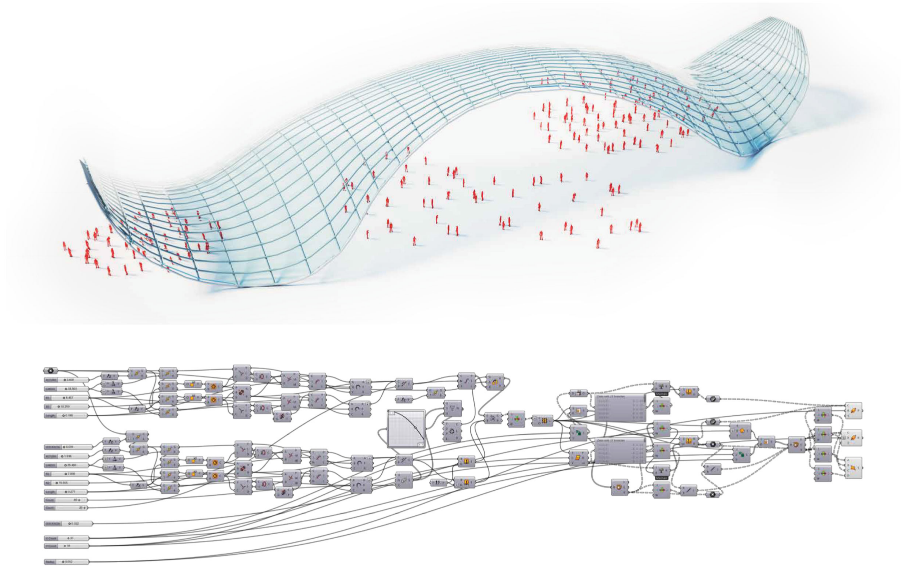


Figure 2.25: *Image from the popular blog "parametric-architecture.com" recommended by *Google© image search* and displaying the architecture as well as the recipe alleviating the effort of processing the visual information (https://parametric-architecture.com/10-grasshopper-plugins-trending-in-the-aec-industry/).*

The procedural nature of PDEs allows users to reuse established solutions, qualifying as procedural knowledge. Unlike textual or graphical information, which demands comprehension and interpretation, an algorithm in PDEs can be extracted and applied straightforwardly, like a cooking recipe. This analogy extends to the influence of visual references in architecture; integrating an attribute from a reference photo into a project requires understanding its composition for effective implementation (see Figure 2.26). In parametric design, the design logic is explicitly outlined in the algorithm, facilitating flexibility through parameter adjustments. However, the range of possibilities remains confined within the algorithm's constraints, highlighting a trade-off between ease of design and the risk of fixation.

Nuancing, experienced designers in PDEs often combine parts of algorithms from various sources to enhance design variation, streamlining the design effort. Nevertheless, translating an analog representation into a parametric model

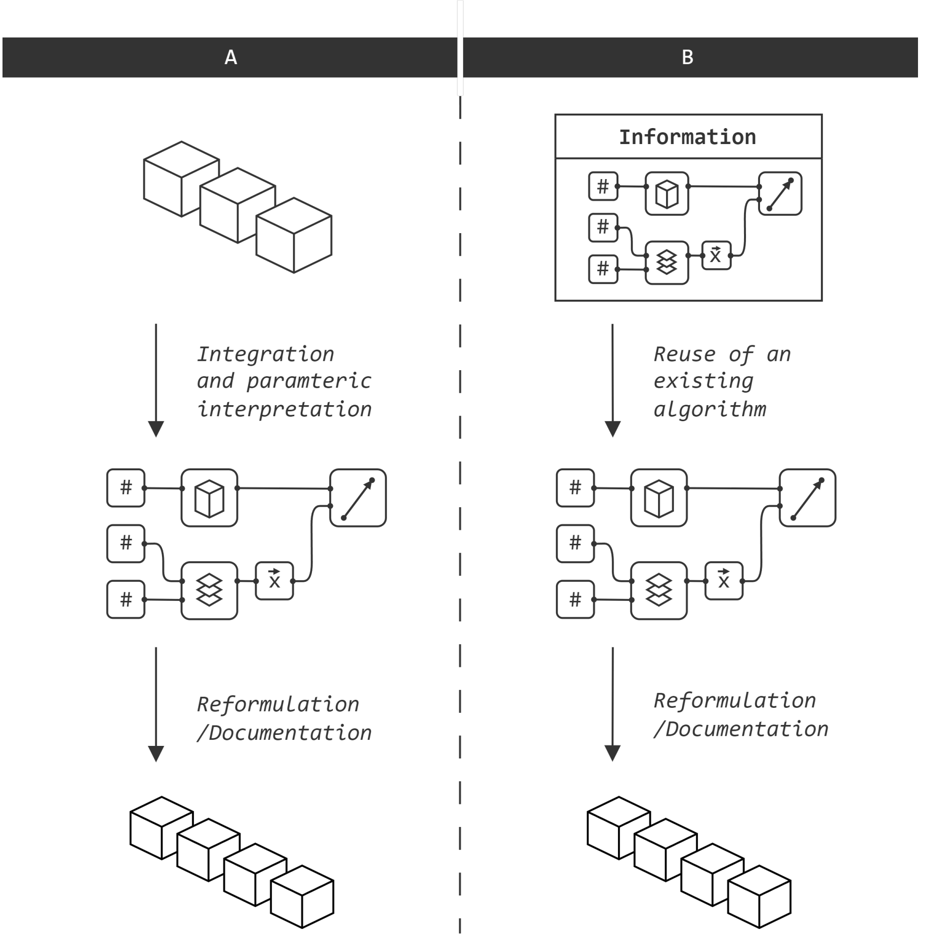


Figure 2.26: *Process A involves parametric thinking while in Process B that effort is alleviated by retrieving the algorithm directly.*

remains a demanding task. Working with PDEs is thus an epistemic action towards embracing complexity in design but also entails additional efforts, leading to specific information retrieval strategies during the design process and the subsequent effort-related behaviors. This applies to both novices and experts, who might rely on pre-existing 'black box' solutions found online.

This observation underscores the potential risk that exposure to ideas poses in leading to fixation. Traditionally, designers were tasked with synthesizing a reflective structure independently. Yet, in retrieving algorithms directly, this synthesis process is effectively circumvented, reducing cognitive effort in subsequent reformulations. Parametric design proves convenient for reformulations. Reformulation 1, within a defined design landscape, translates into exploration through set parameters or superficial modifications of the algorithm (not affecting behavior). However, as Erhan et al. (2017) caution, this can become an overwhelming process due to the multitude of possibilities. Reformulation 2 involves manipulating functions and their connections, altering both the algorithm and the resulting behavior. However, this process might not align with design thinking in the dual process described by Kelly and Gero (2021) as reformulation might be directed at the algorithm without any concern for design. In case of reformulation 3 architects revisit the problem space (H. Jiang et al., 2014), potentially influenced by rule knowledge. For example : while searching for a risotto recipe without finding sufficient information, the individual discovers an easy and detailed recipe for an Indian curry and decides to make that instead. Similarly, architects might set aside a complex project idea in favor of a simpler or more thoroughly documented one. This shift in direction can be attributed to the perceived effort required, influenced by their procedural knowledge or accidental discoveries during the information search. In such scenarios, the provocative stimulus sparking inspiration is characterized by its procedural nature, leading to a lower perceived effort. While Yu (2014) suggests that design tools do not impact the function (F) of design, architects still need to consider design intentions and factor prioritization (Ottchen, 2009). Given the complexity, reformulation 3 and consequently a shift in function F might occur. This shift could lead to abandoning an intended design for an alternative discovered during the design process, thereby redefining the initial design function (F).

2.6.4 Summary

In the realm of architectural design, the transition from traditional tools to advanced digital interfaces has significantly influenced the creative process, particularly through the discontinuities they introduce. Traditional tools, once seen as direct extensions of the architect's thought, are contrasted with digital tools, which tend to be viewed more as aids for documentation, thereby impacting the design process in various ways.

Research on drawing helps in refining the role of tools in the design process. Sketching and drafting embody synthesis and documentation processes. Sketching is crucial for exploring and communicating ideas, contributing to the synthesis of concepts, while drafting, typically linked to documentation, also plays a role in refining design ideas. This duality blurs the lines between synthesizing concepts and documenting them.

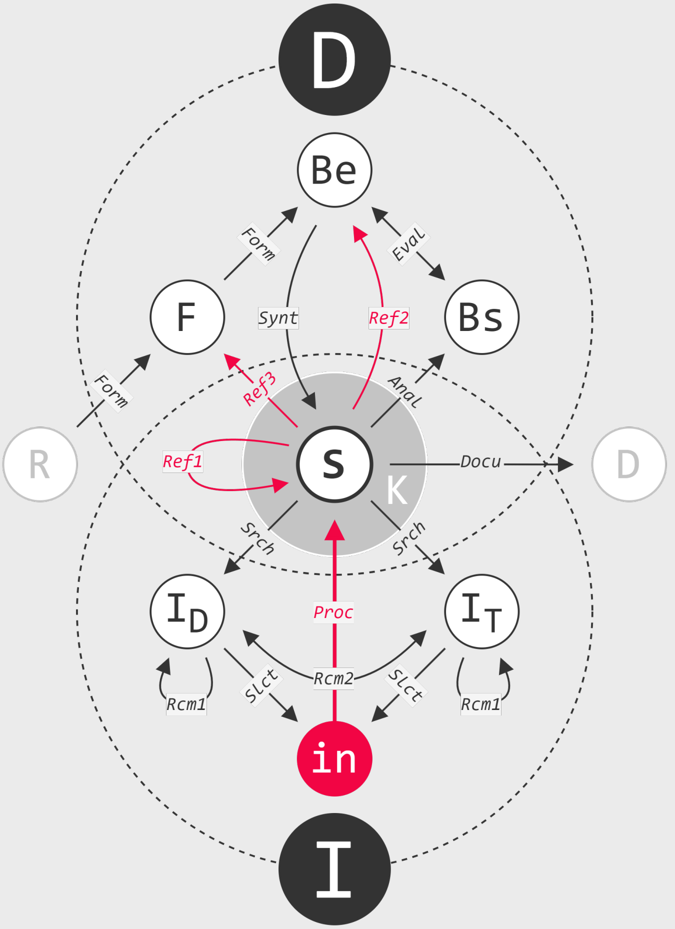
The advent of digital tools has highlighted the risk of discontinuity. While traditional architectural design relies heavily on hand drawing, perceived as more intuitive, digital tools introduce an additional complexity that can lead to a more explicit break between the idea and its realization. "Tool expertise" is becoming an increasingly central issue in generativity moving from idea to structure. Moreover, digital tools have brought a paradigm shift, leading to increased complexity in the design processes and exacerbating discontinuity.

Parametric Design Environments (PDEs) exemplify this shift, moving away from traditional analog drawing methods. PDEs introduce complexities not only inherent to the tool but also arising from adopting new modes of thinking. Transitioning from analog representation to parametric models requires parametric thinking, involving the translation of thought processes into algorithms.

Moreover, PDEs' inherent complexity, potentially leads to a reliance on procedural knowledge. Visual programming tools have become popular for their ability to represent complex forms through sequences of components and relationships. While this approach simplifies the design process, it also risks increasing fixation within the constraints of predefined parameters.

This overview underlines the intricate relationship between architectural tools and design processes, highlighting how the evolution from traditional to digital to computational tools has reshaped the landscape of architectural generativity.

Introduction of the design tool as information class



Design-related and tool-related information are distinguished as two separate but interconnected dimensions. Connections between these dimensions can be formalized through recommendations (Rec2). Specifically, tool-related information is recognized for its potential impact on the design process. Recommendations serve as a pivotal mechanism by which knowledge about tools can influence design decisions, bridging the gap between the two dimensions and facilitating a more integrated and efficient design approach. Similarly, the model recognizes that tool-related information can potentially trigger further reformulations, emphasizing its dynamic influence on the ongoing design process.

2.7 Affordance

The increasing complexity and rapid evolution of architectural tools necessitate architects' reliance on external information sources to keep abreast of developments and enrich their design process. However, the dominance of a limited number of actors in the information search domain raises concerns about potential biases in the representation of architectural reality (Ståhl et al., 2021). These biases can potentially impact architects' decision-making processes and limit exploration of design possibilities.

The concept of affordance provides a valuable lens through which to examine the relationship between tool-related information and the design process. Affordance, as initially proposed by Gibson (1979) refers to the properties and characteristics of an object or environment that suggest possible actions and interactions to an observer. The concept was later expanded to serve research in design (see Figure 2.27) (J. R. A. Maier et al., 2009; Norman, 1988). Within the scope of this study, the idea of affordance is broadened to include design affordance that draws on prior knowledge and its interaction with tools, alongside information retrieval.

2.7.1 Affordances in Human Computer Interaction

The foundation of the concept of affordances was laid by Gibson (1979) as an approach concerned with the analysis of the environment for explaining perceptually guided behaviors. At its core, affordance refers to the potential actions that objects or environments offer to individuals. Importantly, these actions can be seen as both positive and negative, and emerge under specific contextual conditions (Turvey, 1992). The notion of multiplicity is also central, as objects can possess multiple affordances, some of which only manifest under particular circumstances. Warren (1984) proposes the example of stairs, that can become unclimbable if not designed to accommodate varying biometric factors. Affordances extend beyond physical attributes. Time itself becomes a parameter influencing affordances; as people age, their interaction with certain elements, like stairs shifts, exemplifying how age influences affordances of architectural features (Cesari, 2005).

Norman (1988) further advanced the concept of affordance within design and later in the context of Human-Computer Interaction (HCI) specifically user interfaces (Norman, 1999). He first introduced the notion of perceived affordances as actions that users perceive as possible, whether they are practically achievable or not. Norman further introduced the concept of signifiers to improve usability. The International Standardization Organization (ISO) has defined usability as "The extent to which a product can be used by specified users to achieve

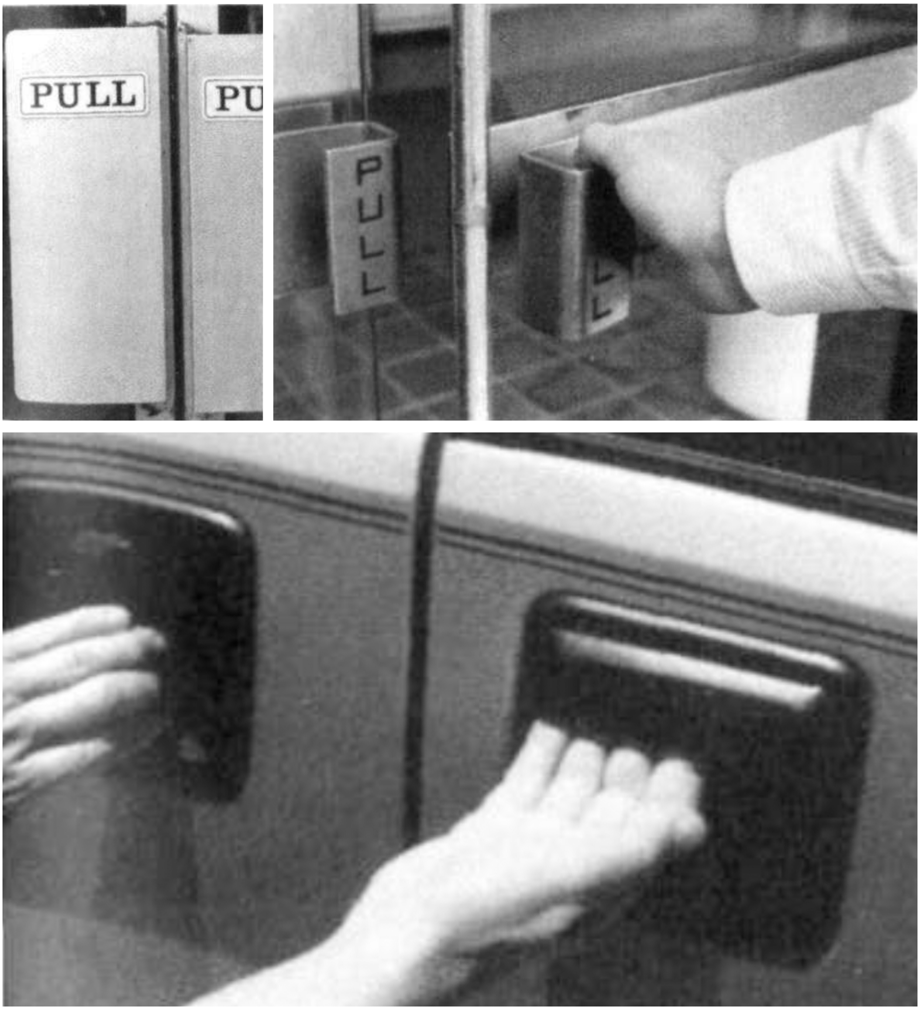


Figure 2.27: *The three photographs illustrate various designs of door hardware and their impact on user interaction. In the top-left photo, large plates are present that conventionally signal a door should be pushed; however, this door actually needs to be pulled, necessitating an additional sign to correct the misleading design. The top-right photo features simple U-shaped brackets, which are a better design in terms of simplicity and ease of use but still carry enough ambiguity that a sign is deemed necessary to clarify the action required. In contrast, the bottom photo shows two handles, neither of which needs a sign yet is always operated properly, affordance is clear. Those examples are extracted from Norman's work (1988)*

specified goals with effectiveness, efficacy, and satisfaction" (ISO, 2018). He suggests improving usability by guiding users through signifiers which are visual or mental cues. These cues, however, are not without their challenges. Hansen (1995) highlights the potential for misinterpretation based on prior knowledge, furthermore the cognitive resources expended on understanding these cues can impede other aspects of a task (Vicente & Rasmussen, 1992).

This discussion resonates with previous observations, integrating the interface as a critical conveyor of information through signifiers, like a tool's own recommender system. It seldom questions fixation due to prior tool-related knowledge, and signifiers that serve as procedural cues that can reduce the effort associated with using a tool. Moreover, usability is characterized not just by the functions a tool offers but also by the range of actions the user has through knowledge, integrating both the potential capabilities of the tool and the user's ability to leverage these capabilities effectively.

Building on this foundation, Norman (1999) delves into the importance of conventions and prior knowledge. Conventions, often influenced by cultural norms, define common interpretations shared by specific groups. While conventions aid users in comprehending product usage, they can be limiting, particularly when users from different cultural backgrounds or generations encounter products designed with a specific group's conventions in mind. Parallel to the concept of convention is the notion of knowledge. Just as there is cultural bias in affordances, there is also a bias related to prior knowledge.

2.7.2 Design Affordances

Maier and Fadel (2001) explored the use of affordance as a foundational concept in engineering design. They found this perspective to be more potent than conventional functional approaches due to its emphasis on user-product interactions and user satisfaction, as opposed to the mere functionality of the artifact (J. R. A. Maier & Fadel, 2003, 2006). Their interpretation of affordance delineates it as a relational aspect between two subsystems, enabling potential behaviors that would be unattainable within the confines of either subsystem in isolation (J. R. A. Maier & Fadel, 2009).

Extending Norman's (1988) understanding of affordances, Maier and Fadel (2009) highlighted the complementary nature of affordance, engaging two entities: the user and the artefact. Consequently, affordance explicates the interactional dynamics of two subsystems and is inherently reliant on the interplay between them, precluding its existence in isolation. When examining Maier and Fadel's (2009) contributions to design and architecture and comparing them with the concept of generativity, a parallel assertion emerges: design occurs at the intersection of two subsystems, namely design affordances and tool affordance (see Figure 2.28) therefore acknowledging the tool's role in building a design structure.

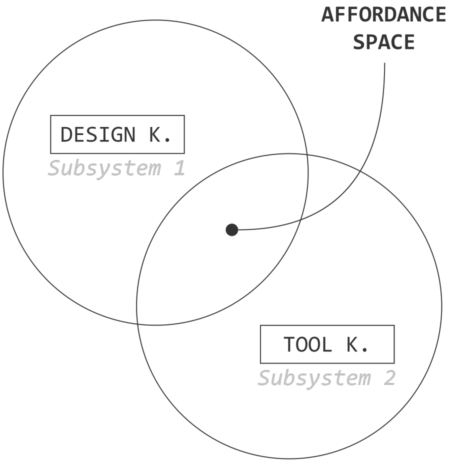


Figure 2.28: *Dual process of Design-knowledge and tool-knowledge expressed as two sub-systems of affordance for design generativity.*

Maier an Fadel (2009) conceptualize architecture as the artifact and its occupants as the end users in their design-artefact-user system. This user-artifact dynamic, however, seems also pertinent in the earlier stages of the design process, where the artifact in question is the design tool, and the user the architect. This perspective is especially relevant when exploring the concept of generativity, which involves the transformation of innovative ideas, shaped by the designer's accumulated knowledge, into tangible entities. Therefore, the "affordance space" for generativity is situated at the intersection of design affordances, rooted in prior knowledge, and the affordances offered by the tools defined by usability.

Moreover, it's important to note that Maier and Fadel, along with Norman, propose that the perception of affordances isn't a direct process but rather an indirect interpretation of information which implies a cognitive component to affordances and underscores the role of information retrieval in perceiving new affordances (Masoudi et al., 2019). This cognitive approach places the architect centrally in the design process, emphasizing their unique interpretation of information, shaped by individual experiences and cultural context such as described by conventions highlighting the intricate interplay between the architect and the corresponding tool affordance (H. Jung et al., 2017; Mougenot et al., 2008; Norman, 1999).

2.7.3 Tool Affordance subsystem

The concept of affordance, defined by Gibson (1979) as the potential of technology to facilitate the intentions of its user, serves as a crucial metric for gauging technology's impact on tasks. For instance, designs derived from working primarily in scale drawings can result in an architecture that is less expressive three-dimensionally than that which results from working with massing models. Scale drawings and physical models have certain potentials that emphasize different qualities of the idea at the expense of others. Because the affordance of the tool influences, channels, and even directs the reasoning that goes on during the design process, it must be chosen carefully to match the task at hand and mitigate discontinuities (Chastain, 1999; Kalay, 2006).

Tools, both physical and digital, are essential for architects to externalize ideas, explore design possibilities, and communicate visions. In architecture, tool affordance refers to the inherent properties of a tool that suggest its potential uses and functionalities (Curinga, 2014). It extends to how tools facilitate or inhibit the design process and influence architectural decision-making. Studies have explored the impact of specific tools on creativity, innovation, collaboration, and communication within architectural teams, highlighting the importance of aligning tool selection with design goals to effectively express architects' ideas (Kalay, 2006; Serriano, 2003; Yu et al., 2013, 2014; Yu & Gero, 2015, 2017). However, these studies often do not explicitly leverage the concept of affordance.

In digital mediums, affordance studies typically focus on user interfaces and their interpretation (Oviatt et al., 2012). Curinga (2014) describes software affordance as a specific type of tool affordance that bridges the gap between the conceptual and tangible aspects of interactive software, enabling potential user interactions with the digital world. However Jung et al.(2017) point out that, like their physical counterpart, software tools are entitled to their own form of materiality. They examine how the materiality of media within their respective ecosystems, either enables or constrains designers in shaping digital artifacts. This perspective considers the material aspects of design tools as affordances inherent to the medium whether it is digital or not.

Distinctive of design affordances, tool affordances are identified as the elements that enable users to take action. And although these tool affordances are ideally designed to be effortless (Still & Dark, 2013), it becomes evident that tools and specially software tools become increasingly intricate. Tool affordance must therefore encompass usability as the extent to which a product can be used by specified users and consider the user's knowledge. Bernal et al. (2015) discuss how complex tools like parametric design environments can offer new possibilities through novel parameter combinations but also note that their inherent complexity can hinder usability, often due to users' lack of prior knowledge.

This complexity may necessitate reliance on information retrieval to overcome usability challenges.

In conclusion, tool affordance fundamentally relies on usability, which is determined by the user's tool-specific knowledge (Norman, 1999). Usability exists within the constraints of the tool's capabilities and is enhanced by a user's understanding of the tool's signifiers. However, with the aid of information retrieval, users' expertise and tool-specific knowledge can be significantly expanded

2.7.4 Information Affordances

Information in architectural design has garnered less attention in comparison to tools. However, in today's digital age, where information is easily accessible, architects rely on external sources to expand their knowledge, gather inspiration, and inform their design decisions. As depicted earlier, research in this area has explored the use of information sources such as books, journals and online platforms in architectural practice (Campbell, 2017; Makri & Warwick, 2010). Given the tool's impact is related to its affordance, a similar assumption can be made for information.

The concept of information affordance is thus proposed in this context. As stated in the section about inspiration, it refers to the inherent potential of external information sources to offer architects valuable insights, design sparks or simply additional knowledge. However, the impact of information on the design process isn't solely determined by its existence. It involves all the layers developed earlier in information retrieval for inspiration such as keyword definition, strategies and selection of stimuli (see 2.4) (Gonçalves et al., 2016).

Moreover, in regards to tool affordance, information affordance will dictate how tool specific knowledge and consequently usability can be expanded. Aish and Hanna (2017) have studied how the availability of information can impede learning in the context of parametric design environments. They classified those challenges as absolute barriers, effective barriers and incorrect pedagogy. Even though the study does not mention the use of information retrieval, results can easily be transposed. Absolute barriers are either related to the inherent tool capabilities, the required functionality simply does not exist, or the functionality exists but is undocumented. Taken further into the context of information retrieval, the information doesn't exist. Effective barriers are described as tool specific, workflow can seem convoluted, a functionality might be hidden or it might have side effects. Additionally, the aspect of discoverability can be expanded upon, indicating that while the necessary information exists, its accessibility hinges on the effort devoted to searching and the user's prior conceptual knowledge. Incorrect pedagogy relates to an incorrect description of the functionality making it difficult to access. The latter eventually contributes to the building of incorrect conceptual knowledge preventing further reuse because of semantic interference (with another tool for example)(Woodbury, 2010).

Therefore, information affordance is heavily dependent on the digital literacy of the user. Jung et al. (2010) introduce the concept of design media affordance to extend affordance to interactive information retrieval systems. These systems are influenced by their recommendation algorithms and the added complexity of AI. Like tools, searching requires expertise and is constrained by the functionalities of the system and, more specifically, the availability of information.

Thus, information affordance encompasses the designer's capacity to navigate through and overcome the biases described in the context of inspiration but also alleviates the issues described by Aish and Hanna (2017) (absolute barriers, effective barriers and incorrect pedagogy) more specific to the information itself. Thus information affordance is dependent to either the design or tool dimensions and can not work as an independent sub-system but rather as the ability to expand design and tool affordance hence knowledge.

The interaction between information affordance and digital platforms is critical. Shared knowledge platforms, like search engines, have a profound impact on architects' information practices. By understanding the interplay between architects' information-seeking behaviors and the affordances presented by these platforms, the model further illuminates on the intricate dynamics of information retrieval in their design process. In accordance with the constructionist approach to information retrieval (see Search As Learning in 2.2), does not appear as a third sub-system but as the expansion of both sub-systems: design knowledge and tool knowledge through a knowledge process (see Figure 2.29).

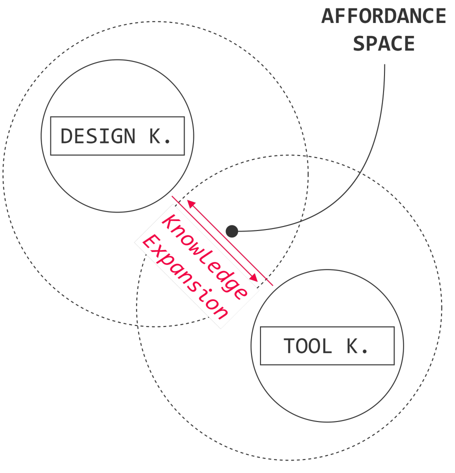


Figure 2.29: *Information affordance appears as the ability to retrieve information to expand either design or tool knowledge. It encompasses digital literacy of the user as well as the existence of information.*

2.7.5 Negative Affordances

The interplay between design, tools and information is established and reveals the negative affordance that can result. Negative affordances are attributes or qualities of a tool or information source that unexpectedly hinder the design process or lead to undesirable outcomes. They arise when biases from inadequate or inappropriate tools or information sources influence the design process. Similarly to the biases leading to fixation, Norman (1999) suggests, the concept of convention plays a crucial role in shaping perceptions of affordances in information retrieval. Biases can manifest as a selection of displayed information and stimuli, similar to signifiers, thus imposing cultural constraints determined by the design of the search engine or information retrieval system itself.

Ultimately, negative affordance manifests as fixation. Although fixation has been previously discussed, viewing it through the lens of affordance provides a structured way to frame fixation across different cognitive processes involved in the proposed model for design encompassing information retrieval. For example, the retrieval of tool related information (Figure 2.30) presents a risk of negative affordance, or fixation, in both tool and design categories of knowledge.

At the design level, the absence of information retrieval poses a risk of fixation due to prior knowledge bias, as architects may rely heavily on existing knowledge and potentially inadequate procedures to minimize effort at the different levels of design (formulation, synthesis,etc. . .). At the tool level, the risk of fixation can emerge at various stages of the inspiration process. This includes the definition of search inputs, which are dependent on prior tool knowledge; the search strategy, which can be influenced by the biases of recommender systems; and the selection of information, which is shaped by the perceived affordances of the stimuli.

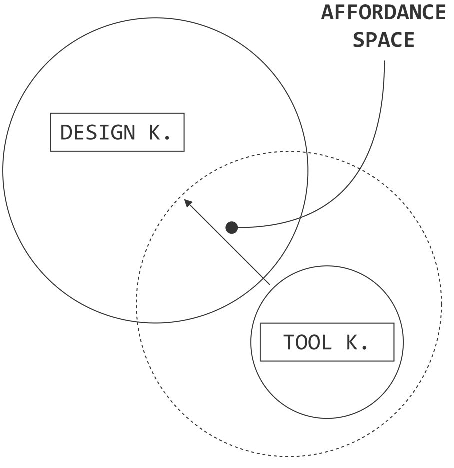


Figure 2.30: *Expansion of Tool Knowledge through IR to afford generativity.*

Understanding how subsystems of affordances interact is crucial for unraveling the complexities that govern the design process, particularly at the structural level of design activity. This understanding also aids in identifying potential negative affordances, those unanticipated attributes of a tool or information source that can hinder the design process or lead to undesirable outcomes. These negative affordances often stem from the perceived effort required, which in turn influences decision-making. Such dynamics can be explored through the lens of cognitive affordance.

Cognitive affordance is closely linked to the concept of effort, which has been seen to play a critical role in every aspect of information retrieval within the design process. Harston (2003) defines cognitive affordance as a design feature that supports or facilitates thinking and understanding. It depends on whether the information inherently aids understanding. Not all information is designed with cognitive affordance in mind. Mismatches between the designer's model and the user's understanding contribute to the Gulf of Execution (Hutchins et al., 1985), a concept referring to the degree of alignment between a user's intentions and their perception of what is possible with a tool or system. Systems with higher cognitive affordance tend to reduce the cognitive effort required and are therefore more user-friendly however the reduced cognitive effort might not align with the user's intent.

In practical terms, developers should prioritize creating interfaces that align with users' cognitive patterns, thereby making technology more intuitive and consequently more useful. However, it's important to acknowledge that major players in the information search business may have different incentives, which brings us back to the critical issue of digital literacy. Digital literacy becomes important in navigating interfaces that may not always align perfectly with cognitive affordance principles.

While the types of knowledge involved in design have been depicted as factual, procedural, and conceptual, cognitive affordance can also be mediated through metacognitive knowledge. This type of knowledge empowers architects to understand not only the content but also the context and the process of their information interactions. By developing digital literacy alongside an understanding of cognitive affordance, architects can better identify and navigate the potential pitfalls of negative affordances in their design process. This dual approach, which integrates both design and tool aspects, leads to more effective outcomes, as architects become adept at using technology in a way that complements their cognitive processes and design needs (Aish & Hanna, 2017; Angulo & Vermillion, 2012; Gonçalves et al., 2013; Kubo et al., 2008; Oxman, 2008).

2.7.6 Summary

In architectural design, the concept of affordance is key to understanding the interplay between tools, information, and the design process. Affordance refers to the potential actions that objects or environments suggest to users, encompassing both positive and negative possibilities. This concept extends to cover the multiplicity of affordances, revealing themselves under specific conditions.

The notion of affordance has been further developed within Human-Computer Interaction to include perceived affordances, which are the actions users believe they can perform with an object, whether or not they are practically achievable. The concept also involves the use of signifiers to guide users, though these can lead to misinterpretations based on prior knowledge and increase the cognitive effort required in tasks.

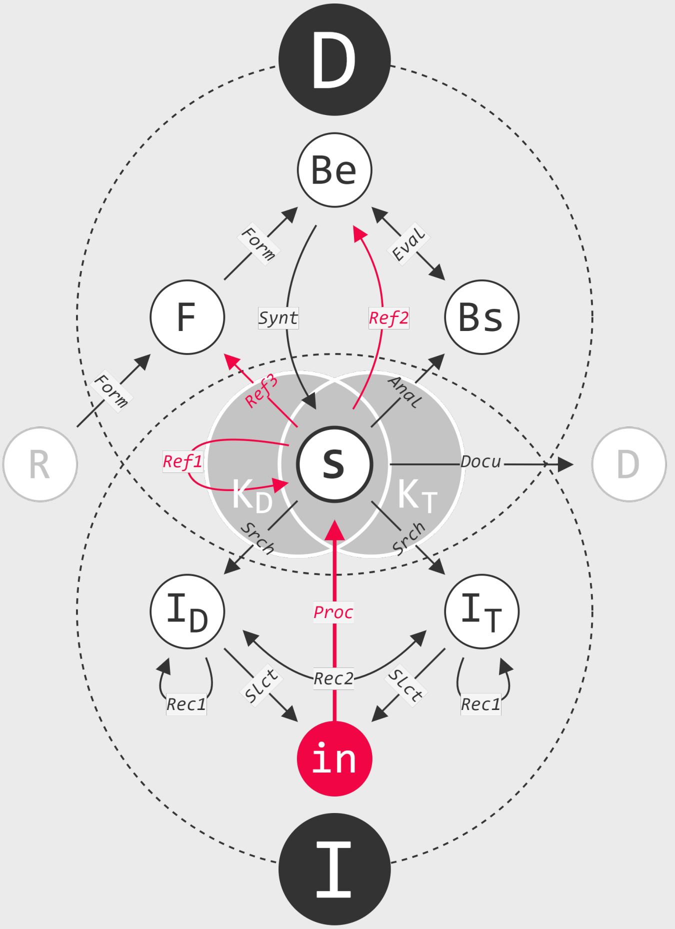
In the context of design, affordance can be seen as a relational aspect between a user and an artefact, emphasizing interactions. In this scenario, the architect is viewed as the user, and the tool is considered the product. This relationship is conceptualized as the intersection of two subsystems: design knowledge and tool knowledge. This relational aspect becomes critical in architecture, where design exists where design knowledge intersect with tool knowledge.

As architectural tools evolve towards digital mediums, the notion of tool affordance expands to how these tools either facilitate or inhibit the design process. The selection of tools that align with design goals is crucial for effective expression of ideas. If alignment with design goals becomes too challenging, the architect must turn to information affordance.

Information affordance in the digital age is centered on the potential of external information sources to offer architects valuable insights in both design and tool knowledge. It encapsulate the available knowledge. However, effective information retrieval heavily depends on the architect's digital literacy and ability to navigate biases with the risk of negative affordance.

Negative affordances, or the undesirable attributes of tools and information sources, arise from the interaction between tools and information. Through the affordance approach, negative affordances can be characterized for both processes. Understanding these negative affordances is essential for architects to navigate the complexities of the design process effectively. Developers should focus on creating interfaces that align with architects' cognitive patterns to enhance usability and intuition in design. However, recognizing that major players in information retrieval may have differing incentives highlights the importance of architects' digital literacy. By combining this with an understanding of cognitive affordance through metacognitive knowledge, architects can effectively navigate design challenges, leading to more efficient and productive outcomes.

Structure at the intersection knowledge sub-systems



*In the same way that design-related and tool-related information are distinguished as two separate dimensions, the model also recognizes the corresponding knowledge dimensions **KD** and **KT** necessary for defining search inputs. At the intersection of these dimensions, design affordance emerges, aligning with the principle of generativity. This principle explicates the need for ideation as well as the means to produce a corresponding entity, hence the inclusion of the tool knowledge dimension. Consequently, structure only exists within that affordance space where generativity is present, underscoring the dynamic interplay between design and the practical constraints of design tools as KT only exists within the range of possibilities offered by the tool.*

2.8 Cognitive load and distribution

Effort emerges as pivotal across all concepts depicted earlier, manifesting as difficulty, a subjective perception of complexity (Li & Belkin, 2008). In architecture, search has been recognized as a source of effort (Snow, 1975), which might explain the preference for brief visual information (MacKinder, 1983). Later, the advent of the Internet has exacerbated that percieved effort by introducing challenges related to managing vast amounts of information (Rhodes, 1998). Conversely, the preference for searching over recalling information underscores a strategic shift towards more accessible knowledge acquisition (Hicks et al., 2002).

In the realm of Interactive Information Retrieval, learning is viewed as a cognitive effort influenced by the cognitive complexity of tasks, leading to a preference for procedural knowledge in creative tasks (Urgo et al., 2020). Effort considerations extend to defining search inputs, where there is often reluctance due to the perceived investment required (Dosso et al., 2020), to the activities involved in searching and interactions with search systems (Chan et al., 2015; Royo et al., 2021). Effort is also a critical criterion in the selection process (Gonçalves et al., 2016).

The concept of effort relates to the accessibility of information, contrasting restrictive versus expansive information requirements (Purcell et al., 1993). Lesser effort can potentially lead to fixation (Ozkan & Dogan, 2013). Recommender systems prompt users towards low-effort searches (Tollon, 2021), a trend mirrored with design tools that encourage effortless practices (Claeys, 2023). Yet some tools, notably Parametric Design Environments (PDEs) tend to introduce new difficulties (Yu et al., 2014).

Finally in the context of affordance effort or rather the lack of it has translated into cognitive affordance, a design feature meant to facilitate the use of a function by alleviating the effort associated with it. The overall generative affordance or the landscape of design possibilities, considering generativity and therefore passed ideation, only exists within the scope of cognitive affordance. Indeed, if a specific task within the design process is perceived as requiring too much effort, it falls outside of cognitive affordance and, consequently, won't appear in design propositions.

In order to contextualize effort, this conceptual framework adopts the concept of cognitive load. Analyzing cognitive load and its potential for manipulation offers a direct approach to exploring the concept of cognitive affordance, particularly through the lens of Cognitive Load Theory (CLT). CLT elucidates how working memory constraints impact retrieval decisions in the design process, offering insights into optimizing the use of design tools and information retrieval strategies. This perspective aims to enhance the understanding of the cognitive underpinnings of information retrieval that influence design outcomes.

Working memory is a mental workspace for temporarily holding and manipulating information. Its limitations are critical in determining how designers manage complex tasks such as balancing spatial, structural, and aesthetic considerations (Baddeley, 1992). Effective management of cognitive load involves minimizing irrelevant cognitive processing and optimizing processes necessary to learning within the confines of working memory capacity (Van Merrienboer et al., 2006). However, the cognitive load imposed by a task can sometimes exceed working memory, leading to errors or task abandonment (Safin et al., 2008). To counter this, designers often use tools as cognitive supports.

Working memory can be understood as a system delimited by the functional relationships among the elements that participate in it (Hollan et al., 2000). Up until now, tools have appeared to be an essential element. Sketching for instance is argued to be beneficial in offloading the designer's visuo-spatial working memory and freeing up cognitive resources during design tasks (Suwa et al., 1998). That is, sketches serve as an external memory where visuo-spatial features and relations may be stored, inspected and manipulated as opposed to maintaining them in working memory which could lead to a very constrained design process (Suwa et al., 1998). In contrast, digital tools can contribute to an additional cognitive load, making tool expertise a key factor in reducing overall cognitive burden. This is especially relevant in the context of complex tools like PDEs. The action off-loading working memory is studied more specifically within distributed cognition.

2.8.1 Distributed Cognition and Epistemic Actions

The concept of distributed cognition suggests cognitive processes can be spread across individuals and external structures (Hollan et al., 2000). It involves coordination between internal and external elements and can be distributed over time, allowing the products of earlier events to influence later ones (Hollan et al., 2000). This distribution of cognition highlights how representational states and informational flows around media carrying these representations are central to design work. It connects people, problems, and tools into a cohesive unit of analysis, making it an ideal to understand the artefactual, social, and cultural dimensions of architectural work when considering interactive information retrieval.

Distributed cognition extends the scope of what is considered cognitive beyond the individual to include interactions between people and resources, and materials in the environment (Hutchins, 1995). It considers representational artifacts such as the design structure (S), tools and other individuals as part of a larger cognitive system that assists in the thinking process (Perry, 2003).

In this context, epistemic actions refer to operations carried out to uncover information that aids cognitive processes, or actions taken specifically to facilitate cognition (Kirsh & Maglio, 1994). In the realm of design, such actions might include sketching, building models, or manipulating materials, whether in physical or digital formats. These activities serve as a form of "external memory," effectively reducing the cognitive load on working memory by providing a tangible, external platform for ideation and thought processes. This externalization is integral to the concept of generativity, as it transforms abstract ideas into representational entities that can be interacted with and iteratively refined. These physical actions are not merely reactive to cognitive decisions but are themselves integral components of the cognitive process. They actively participate in shaping the thought process by redistributing cognitive load, thereby facilitating the design process (Claeys, 2018).

Through these epistemic actions, designers have the ability to externalize and manipulate their thoughts, thereby conserving cognitive resources for higher-level abstract reasoning (Casakin & Goldschmidt, 1999). The use of analogy exemplifies distributed cognition as designers draw on visual references in cross-domain knowledge to inspire and generate new ideas (Casakin, 2007). In that case the entity is shared through a collective mind as information to build upon. Moreover it is interesting to consider design tools as entities for distribution that eventually require further epistemic actions to be effective.

Tools are fundamental to distributed cognition in architecture, as much of the information distribution occurs through visual representations. However, as previously noted, tools can impose a significant cognitive load, a burden that has increased with the advent of digital tools. Figure 2.31 offers a simplified depiction of how a tool can alleviate some of the task effort but simultaneously introduce its own set of demands. This additional effort, in turn, is often mitigated by accessing information through epistemic actions such as information retrieval, which can eventually impact the design process.

Consider the example of an architect tasked with designing a complex, non-standard form for a building. He is advised that the simplest approach is to study the form through 3D-printed models, which would allow for easy sharing with colleagues and clients for feedback. However, if the architect lacks experience with 3D printing, this suggestion introduces a new layer of cognitive demand as the architect must now invest effort into researching 3D printing techniques. If the perceived effort is deemed too high, the architect might opt to switch to a more familiar geometry, relying on well-known and simpler techniques such as cardboard cutting and assembling. By reverting to more familiar methods, the architect reduces cognitive strain but also limits the design potential to what he can afford cognitively (hence cognitive affordance).

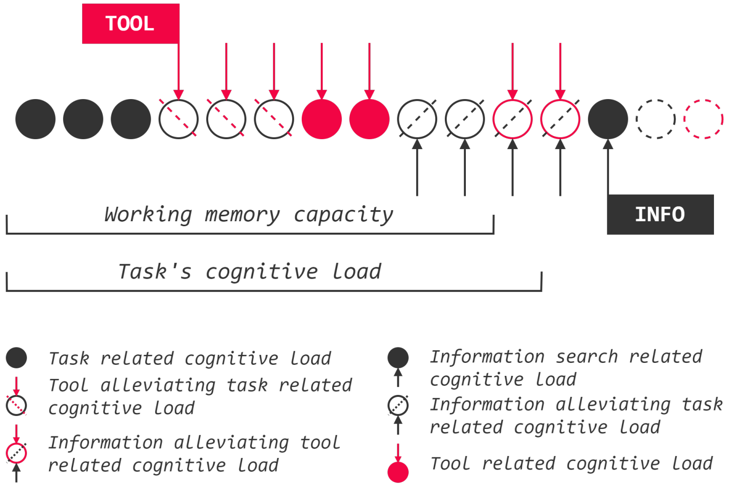


Figure 2.31: *Simplified representation of cognitive load management using tools for visual cognitive distribution. The tool alleviates part of the design task cognitive load however the tool can require some cognitive investment as well. The subsequent cognitive load can then be alleviated through information retrieval that can also play a role in alleviating part of the design task effort directly. Finally, information retrieval also represents an effort. The overall cognitive load must stay within the working memory capacity.*

2.8.2 Cognitive Load in design

CLT is frequently applied in the field of instructional design, particularly in educational contexts. This theory underscores the importance of structuring information delivery to reduce extraneous load, the unnecessary effort associated with searching for and processing information. Traditionally, the responsibility of instructional design in education has been the domain of educators. However, the expanding access to information has shifted the focus towards fostering digital literacy and promoting autonomous learning. This shift reflects an adaptation of instructional design principles to empower self-learners. Self-Directed Learning (SDL), a subfield emerging from CLT, accentuates the importance of metacognitive abilities and principles that support autonomous learning endeavors.

A comprehensive retrospective by Sweller (2019) delves into the various cognitive effects studied within the framework of CLT, particularly focusing on its impact on working memory and the facilitation of knowledge construction. The essence of these facilitators lies in reducing extraneous cognitive load, essentially making information more engaging and less burdensome to process. Applying CLT principles suggests a need for carefully structuring learning materials and activities. The goal is to minimize unnecessary cognitive load while maximizing the effectiveness of the learning process (Mayer & Moreno, 2003; Sweller et al., 1998).

These approaches not only make the learning process more efficient but also align with the evolving needs of learners in a digitally rich and information-heavy environment. They underscore the necessity of adapting instructional design to cater to both the cognitive limitations and the expanding autonomy of learners, particularly in fields like architecture where the interplay of information, design knowledge, and technical knowledge is complex and dynamic. Within the framework of CLT, a variety of cognitive or instructional effects have been explored to assist educators in crafting their educational content more effectively (Sweller et al., 2019). In the realm of self-regulated learning, these empirical findings lay a foundational layer of metacognitive knowledge that helps differentiate between information and its actual relevance, guiding learners in navigating the vast seas of available information more cautiously.

2.8.2.1 Instructional effects

Several key effects identified within CLT have profound implications for instructional design, resonating and expanding upon ideas previously explored in Interactive Information Retrieval (IIR) and design. The worked example effect, highlights how providing complete solutions for study helps focus learners' attention and develop problem-solving skills. This approach contrasts with conventional problem-solving tasks by directing attention to problem states and solution steps. Worked examples are very much procedural information and infer high risks of fixation. Furthermore they are highly effective for novice learners who lack conceptual prior knowledge. The challenge lies in designing these examples to be informative without overwhelming learners, a balance critical in disciplines like architecture where complexity and creativity are paramount (J. R. Anderson et al., 1997; Renkl, 2014). Consequently architects should be aware of their attractiveness when looking for inspiration. The procedural aspect suggests even more fixation risk in PDEs due to effortless reformulation 1 (R1).

In contrast, Paas and vanMerrienboer (1994) introduced the variability effect, which, despite initially increasing cognitive load, ultimately benefits learning by enhancing the discrimination between relevant and irrelevant features. This effect underscores the importance of designing instruction to first reduce extraneous load, then strategically increase germane load within manageable limits. In architectural design, embracing variability could therefore help build conceptual knowledge and alleviate fixation albeit for a relatively high cognitive investment.

Working memory can become depleted after sustained cognitive exertion, leading to a diminished capacity for further resource allocation (Chen et al., 2018). This phenomenon is particularly relevant when considering the extensive duration often required for design tasks. The concept of multiple sessions introduces an additional layer of complexity to this issue (Li et al., 2020). Those often relate to another popular concept : motivation. While some view motivation as the anticipated investment of mental effort, research indicates that the level of motivation reported prior to a task does not necessarily predict improved outcomes. Others suggest that motivation is influenced by cognitive load, arguing that tasks perceived as overly demanding may deter motivation. Ultimately, motivation is linked to the amount of time spent on research; more time devoted to information search can lead to greater knowledge accumulation, making individuals more likely to develop conceptual understanding (Feldon et al., 2019).

Finally, the self-management effect posits that learners can be taught to apply CLT principles to manage their cognitive load more effectively (Sithole et al., 2017). This approach becomes increasingly relevant in an era where information is ubiquitous and not always curated for quality. Teaching students to evaluate information critically is crucial for fostering better learning. However, this effect doesn't directly address the selection of learning activities, a gap that self-regulated learning (SRL) aims to fill.

2.8.2.2 Self Regulated Learning

Unlike the self-management effect, which emphasizes learning cognitive load principles aligned with metacognitive knowledge, SRL concentrates on the selection of appropriate learning tasks and resources. This focus on information literacy is particularly important in contexts rich with opportunities for self-teaching (de Bruin & van Merriënboer, 2017). The emergence of SRL research was motivated by observations of learners' difficulties in regulating their own learning processes, highlighting the need for strategies that enhance cognitive resource management (Bjork et al., 2013).

Designers adept in SRL strategies demonstrate proficiency in managing their cognitive resources through metacognitive planning, monitoring, and evaluation. This capability is crucial in the iterative nature of architectural design, which involves repeated cycles of evaluation and redesign (Zimmerman, 2002). Such strategies are indispensable for supporting lifelong learning in an information-rich and fast-evolving society, highlighting the necessity for task involvement and precise resource allocation. SRL's emphasis on the strategic selection of learning tasks and resources goes beyond mere content engagement, addressing learners' challenges in regulating their learning with accuracy (Bjork et al., 2013; Nugteren et al., 2018).

To further enhance SRL strategies, the adoption of the 4C/ID model is proposed. This model recommends withholding highly interactive supportive information during task performance, allowing learners to construct and activate knowledge structures in long-term memory (LTM). Such structures can then be more efficiently accessed and applied within working memory, significantly reducing the cognitive demand compared to processing externally presented complex information during task execution (Sweller et al., 2019). A particularly notable skill developed within this framework is the ability of self-learners to generate keywords, which facilitates the retrieval of constructed cognitive structures and exemplifies the practical application of SRL strategies (de Bruin & van Merriënboer, 2017).

The integration of distributed cognition, epistemic actions, and cognitive load principles offers profound insights into the complexity of design cognition. Designers' adaptive strategies, whether applied consciously or subconsciously, manifest the principle of least effort, aiming to balance cognitive demand with capacity. These strategies include the selection between simple and complex tools, visual and abstract representations, and the exploration of familiar versus novel approaches. Such decisions are pivotal for fostering efficient and innovative design thinking, reflecting the core objectives of SRL in architectural practice (Berthoz, 2012; Zipf, 2012).

This section illuminates the cognitive foundations underpinning architectural design, showcasing how designers adeptly navigate the intricate interplay between cognitive load, knowledge creation, and information processing. The cohesive integration of epistemic actions and distributed cognition provides a comprehensive view of the design process, aligning closely with the practicalities of architectural practice (Casakin & Goldschmidt, 1999). Viewing this through the lens of Self-Regulated Learning (SRL) enhances comprehension of how architects can manage their cognitive resources efficiently. This approach facilitates sustained learning engagement within a field marked by ongoing change and complexity, emphasizing the importance of cognitive strategies for professional growth and adaptability in architecture.

2.8.3 Summary

Exploring the intersection of cognitive affordance and architectural design, the application of Cognitive Load Theory (CLT) is proposed to understand how effort influences designers' capability to effectively navigate through vast amounts of information. Working memory, the mental space for processing and manipulating information, is at the core of this discussion. Having a limited capacity, the management of cognitive load essential in the design process.

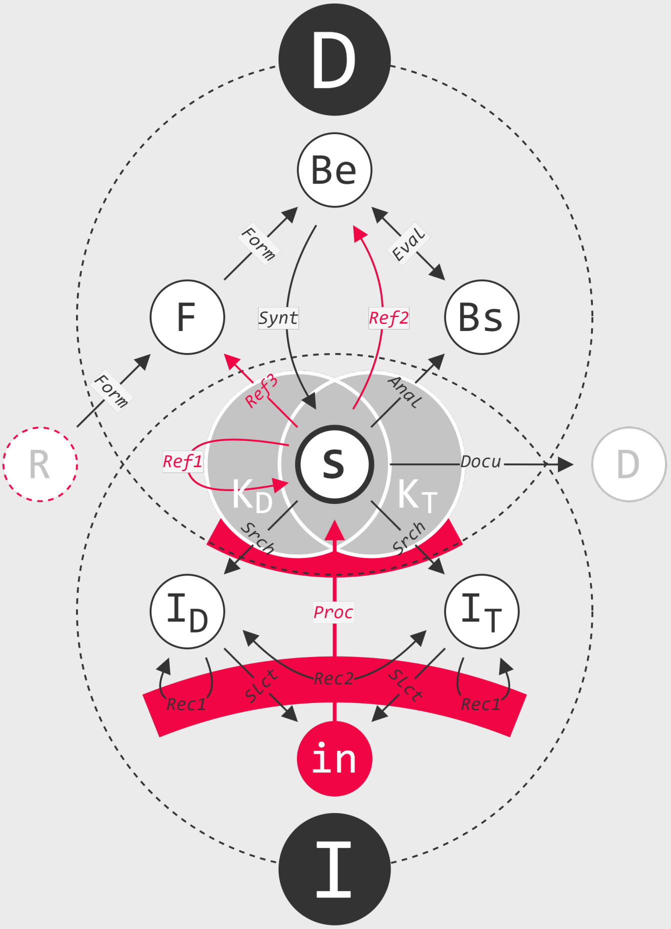
The cognitive load imposed by design tasks can sometimes surpass an individual's mental capacity, potentially leading to errors or task abandonment. Designers, therefore, rely on various tools and strategies to mitigate cognitive overload. One notable strategy is the use of sketches, which serve as an external memory aid, offloading the visuo-spatial demands from working memory and freeing up cognitive resources for other aspects of design. However, the introduction of digital tools has added complexity, as their use can contribute additional cognitive load.

Distributed cognition further expands on this concept by suggesting that cognitive processes extend beyond the individual to include interactions with external elements and tools. This approach underscores the significance of representational states and informational flows, facilitating a comprehensive understanding of the design process as a collective cognitive effort. Epistemic actions are the physical actions taken to facilitate distributed cognition. Whether sketching, building models, or manipulating materials, these actions externalize cognitive processes.

CLT's application extends to instructional design, emphasizing the structuring of information delivery to reduce extraneous cognitive load and enhance learning efficiency. This principle is increasingly relevant in today's information-saturated environment, prompting a shift towards fostering digital literacy and autonomous learning. Self-Regulated Learning (SRL) emerge as crucial line of research in this regard, focusing on the autonomous selection of learning tasks and resources. SRL emphasizes metacognitive strategies such as planning, monitoring, and evaluating one's learning process, which are indispensable in managing cognitive resources effectively.

Ultimately, the integration of cognitive load management strategies, distributed cognition, and epistemic actions provides deep insights into the cognitive underpinnings of architectural design. It reveals how designers navigate the challenges of information processing, knowledge creation, and cognitive load management, ensuring efficient and innovative design outcomes. This holistic view of the design process, grounded in cognitive science, underscores the importance of cognitive resource management in fostering a sustainable and productive design practice.

Integration of meta-cognitive strategies through SRL



In the model, effort is conceptualized as cognitive load, present in every activity within the design process. Metacognitive strategies are identified as key mitigators of information impact, particularly within the processes related to inspiration. These strategies are depicted in the model to illustrate how they help manage the cognitive load induced by various design-related activities. The primary objective is to study the interplay between cognitive load and information, exploring how designers employ metacognitive strategies to optimize their cognitive resources and effectively navigate the information-rich environment of the design process.

3 *Research Design*

This chapter delineates the structured approach employed to investigate the impact of information retrieval in early stages of architectural design. Central to this inquiry are the aims and hypotheses formulated to guide the research, and are articulated through clearly defined research statements. These research statements serve as the foundation for the adopted methodologies.

The research methodology section details the multifaceted strategies used to collect data, which include surveys, interviews, and log analyses. Each method is chosen for its ability to provide insights into the different aspects of how architecture students retrieve and utilize information in their work. Surveys and interviews help capture subjective experiences and perceptions, while log analysis offers objective data on user interactions within parametric design environments.

Data analysis is approached through a combination of quantitative and qualitative methods to foster a comprehensive understanding of the collected data. Quantitative analysis allows for the measurement of patterns and occurrences, whereas qualitative analysis, including coding, thematic analysis, and content analysis, delves into deeper insights into the meanings and interpretations behind the data.

3.1 Aim and Objectives

The primary aim of this research is to investigate the impact of information retrieval on the early stages of the architectural design process, with a particular focus on how design tools, specifically parametric design environments, mediate this interaction. To explore these dynamics, a conceptual framework was developed through an extensive literature review. This framework integrates theories from diverse domains, including Interactive Information Retrieval, Design, Tools, Search Systems, Affordance, and Cognitive Load. It serves as the foundation for understanding the complex interplay between these elements and their influence on architectural design.

The literature reveals a scarcity in the examination of information retrieval within the field of architecture, identifying visual information as a primary focus but also highlighting the need for further inquiry. Research on Interactive Information Retrieval frames information searching as a critical learning mechanism and categorizes specific tasks according to their complexity and learning orientation. Among these, "create tasks" are particularly relevant to design activities. This area of study introduces a discussion on types of knowledge, factual, procedural, conceptual, and metacognitive, and advocates for the use of procedural knowledge in creative tasks. Procedural knowledge is favored due to its efficiency and the reduced cognitive effort it requires, making it particularly suitable for the demands of design-related tasks.

It is crucial to distinguish between knowledge and information in this context. Knowledge is acquired through a knowledge process of information. What designers search for is information, which is ultimately consolidated into a broader network of conceptual knowledge, itself necessary for the search activity. Searchers need to have some understanding of what they are looking for, which underscores the importance of having a robust conceptual knowledge base that informs and directs the information retrieval process.

The notion of design is further explored through the lens of generativity, with the Concept-Knowledge (CK) theory elucidating the interaction between concept, knowledge, and, by extension, information. However, CK theory does not fully detail the processes within the concept space and information space. In contrast, the Function-Behavior-Structure (FBS) framework provides a more comprehensive explanation of the concept space by detailing the design process in alignment with generativity, particularly emphasizing reformulation as a crucial mechanism. It identifies structure S as foundational in the design process. Moreover, the framework positions structure S not only as a critical element for knowledge creation but also as pivotal for integrating information. Consequently, S is situated at the confluence of design and information, forming the central element of the model (see Figure 3.1).

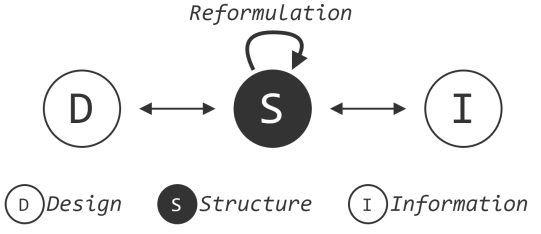


Figure 3.1: *Structure at the intersection of design and information retrieval.*

The information space within this framework is characterized by the inspiration process, which includes the definition of search inputs, the search strategy, and the selection of stimuli. Thus the framework effectively integrates design with related information retrieval processes. Search systems, notably shaped by their recommendation mechanisms, play a pivotal role in this integration. Their recommender systems serve to alleviate the cognitive demands inherent in information retrieval but can also introduce biases. These systems thus potentially impact each phase of the inspiration process by limiting the range of options based on predicted user preferences, or statistical and cultural biases, thereby influencing the overall design outcomes.

In parallel, the framework proposes the consideration of design tools as the interplay with information might further highlight discontinuities in the process. These tools, especially complex ones like Parametric Design Environments (PDEs), can reduce cognitive load by streamlining specific tasks, yet conversely, they can increase it due to their inherent complexity. The requirement for prior expertise with such tools may necessitate a higher level of effort, potentially affecting the inspiration process as it would translate into tool specific information retrieval. This dual role of design tools, as both facilitators and complicators of cognitive processes, underscores their potential impact on both the synthesis of structures and the reformulation processes within architectural design.

Affordance and more specifically its subsystem model further emphasizes the role of tools in architectural design. Generativity, which encompasses ideation and the synthesis of a corresponding structure through a specific tool, dictates that such a structure can only exist within the realm of usability and eventually tool knowledge. Thus following the notion of subsystems in affordance, S exists at the intersection of 2 subsystems : design and tool knowledge. Additionally, instead of appearing as a third independent subsystem, information serves to expand these existing subsystems by enhancing affordance. However, the mere availability of information does not guarantee its accessibility; this is where digital literacy becomes crucial. The ability to effectively navigate through available information relies on digital literacy skills, and require additional effort.

Ultimately, search behaviors in the design process are fundamentally driven by effort, conceptualized as cognitive load. These behaviors are anticipated to align with principles of Cognitive Load Theory, which posits that in instructional design, efforts should be made to minimize extraneous cognitive load to enhance learning efficiency. However, designers often operate autonomously, making them responsible for the information they choose to engage with. This autonomy carries the risk of prioritizing the reduction of effort without specificity, potentially leading to suboptimal learning and design outcomes.

The model developed synthesizes various established theories into a conceptual framework that examines the role of Information Retrieval (IR) in the early stages of the architectural design process. By integrating information retrieval as an essential element, this framework augments traditional design theories, offering a more holistic approach to design. Central to this framework is the premise of generativity, which encompasses ideation and the ability to materialize ideas, underscores the essential role of tools in the design process. Historically, the impact of tools on design outcomes has been ambiguous, with studies showing varied results. However, this model provides a nuanced perspective by emphasizing that the influence of tools is most significant when considered in conjunction with information retrieval.

The primary objective of this research is to examine the impact of Information Retrieval in early stages of the Architectural Design. As the conceptual framework has been established, the next step involves its application. This phase is critical to verify the framework's pertinence in practical settings (Jabareen, 2009).

First, based on the conceptual framework, the central research question is refined to "*How does inspiration impacts the reformulation process in architectural design in the digital age*." This question examines inspiration as the act of gathering and transforming information into actionable knowledge within the design process. Reformulation represents the effect of information on design, centralizing the concept of structure as outlined in the conceptual model. The context of the digital age encompasses the utilization of digital tools and search systems, including the impact of recommender systems. However, the proposed framework extends beyond digital realms to serve all forms of information retrieval, such as through the internet, colleagues, or books and their subsequent modalities. Similarly for the design tool, the framework considers any tool for synthesis and acknowledges the complexity introduced by digital tools, illustrated with parametric design, showcasing the model's adaptability to the diverse tools and methods employed by architects beyond traditional means.

The established framework forms the basis for the hypotheses of this study, with effort identified as a recurrent factor of impact related to the information itself. In Interactive Information Retrieval, effort is associated with the type of knowledge and, consequently, the type of information necessary to integrate in order to complete a task. By extension, the information is either factual, procedural, conceptual or metacognitive. Although empirical findings in architecture and design have explored the medium of information, these have not yet been systematically tied to a theoretical framework. Research finds that visual information predominates, facilitated by its ease of integration within the inherently visual nature of architectural work. This includes images from the internet, diagrams from books, sketches from colleagues, or videos. However, focusing on the source of information rather than just the medium highlights effort considerations more effectively; for instance, acquiring information directly from people often requires less effort than searching online or in books. This focus also acknowledges the multimodal nature of information sources, such as magazines that combine images with textual explanations, akin to a colleague who sketches while explaining. Additionally, This study proposes that the design structure emerges at the nexus of design knowledge and tool knowledge, expanding into their respective information spaces. Consequently, a third dimension of information, its category, categorized into design or tool information, is introduced. Those distinctions help defining information by its nature, incorporating its type, source, and category, leading to inquiries about the characteristics of retrieved information their recommendations and its implications for design.

Focusing on the nature of information allows the consideration of the tool as a category and recommender system as embedded into the inspiration process. Therefore the nature of information is considered in the study of the impact of information retrieval on the design process.

These inquiries can be further segmented into examining:

1. What is the impact of information categories on the design process, and how does the prevalence of tool-related information retrieval demonstrate the influence of tools within the conceptual framework?

2. How do various information sources influence the design process, particularly in shaping design and tool-related knowledge, given the significant impact of visual content and the evolving relationship between sketches, videos, and recommendation systems within parametric design environments ?

3. How does the management of cognitive load through information retrieval systems affect the design process, particularly in the context of parametric design environments, and what are the implications for educational practices in architecture ?

These questions aims to dissect the multifaceted impact of information retrieval on architectural design, shedding light on how various aspects of information—its type, source, and class—affect the architectural design process. Furthermore their interrelation is analyzed.

3.2 Research methodology

This study employs a concurrent transformative mixed methods approach, blending both quantitative and qualitative research methodologies grounded in the conceptual framework, to examine the impact of information retrieval on architectural design. The methodological approach encompasses questionnaires for quantitative analysis, alongside interviews and student logs for gathering qualitative insights. This comprehensive approach allows for a nuanced exploration of how information retrieval influences architectural design, capturing a wide range of perspectives and data types to provide a multifaceted understanding of the phenomenon.

Creswell (2014) defines that approach by effectively integrating both triangulation and embedded models within a transformative framework. The triangulation model compensates for methodological weaknesses by concurrently collecting quantitative and qualitative data, thereby facilitating the comparison of these data sets during the research phase. This approach enhances the robustness of the findings by providing a balanced view that mitigates the biases inherent in using a single method. On the other hand, the embedded model addresses the challenges of multidisciplinary research by allowing for a composite assessment. It enables side-by-side data presentation, which is particularly useful in catering to the diverse research questions posed in the study. Together, these models strengthen the methodological framework and ensure a thorough exploration of the multifaceted issues under investigation.

Protocol analysis serves as the foundational basis for developing the methodology for evaluating qualitative content in this research. It is a preferred method for investigating design activity and is frequently referenced within the theoretical frameworks discussed in the literature review. Following the classification of Dorst and Dijkhuis's (1995) the research follows both process-oriented and content-oriented approaches. This dual approach facilitates a segmented yet comprehensive examination of the qualitative landscape, enabling an in-depth analysis of the design process and the content it generates, thereby offering a holistic view of how architectural design activities unfold.

The concurrent transformative model may take on the design features of either a triangulation or an embedded approach. The mixing of the data would be through merging, connecting, or embedding the data. This model benefits from situating mixed methods research within a transformative framework, enhancing its appeal for this study since the conceptual framework guides the inquiry. The transformative aspect emphasizes change and addresses complex questions by integrating diverse methodologies, aligning with the study's goal to deeply understand the impact of information retrieval on architectural design. The details of the research design plan are illustrated in Figure 3.2.

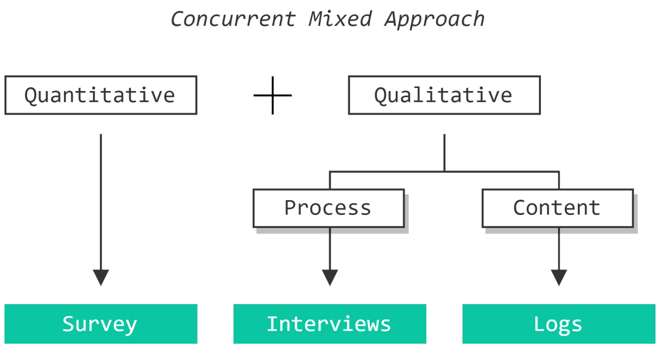


Figure 3.2: *Summary of the mixed-methods approach to research design.*

In summary, the quantitative and qualitative data collection will be presented in separate sections, but the analysis and interpretation will combine the two forms of data to seek convergence or similarities among the results aiming for insights into the coherence between different data forms. Ultimately the goal is to foster critics to the conceptual framework and the corresponding model and eventually propose changes, reflecting the transformative essence of the approach.

3.2.1 Data collection

The experiment setup involved collecting data from an elective class called "Introduction to Computational Design" within the Master of Architecture program at University of Liège. The class focused on teaching computational design principles using the Parametric Design Environment (PDE) Grasshopper©.

A concurrent sampling was thus used for both quantitative and qualitative approach. This research spanned two years and involved two cohorts, each consisting of 17 students. These students, who had no prior experience with Grasshopper© or parametric design, were organized into 7 teams each year (14 in total) due to class logistics. This arrangement not only facilitated data collection but also reflected real-world collaborative scenarios common in architecture, where teamwork is integral. In Table 3.1, the anonymized IDs of all students are listed alongside their respective groups. Additionally, all participants were provided with an informed consent form, which they signed to confirm their understanding and agreement to participate in the study.

Selecting students as the primary dataset offers a unique perspective to explore

Table 3.1: *Each student was assigned an ID number to maintain anonymity throughout the study. The table displays these IDs alongside their corresponding groups, which are designated by letters. This arrangement includes students from both the 2021 and 2022 classes.*

Year/Group	A	B	C	D	E	F	G
2021	1; 2; 3	4; 5	6; 7	8; 9; 10	11; 12; 13	14; 15	16; 17; 18
2022	1; 2	3; 4	5; 6; 7	8; 9; 10	11; 12	13; 14; 15	16; 17

self-regulated learning in the context of architectural design activity within architectural education. These students have an academic background in design theory, but their practical experience is relatively limited, making them ideal subjects for examining how novices adapt to contemporary digital tools in architectural practice.

The requirement for students to use specific digital tools not only facilitates their learning but also prepares them for the evolving landscape of technology that professionals in the field will inevitably encounter. This enforced adaptation underscores the importance of digital literacy, particularly as older generations may not fully recognize the need to stay updated with new software tools. Moreover, the financial aspect of using students as a study group is significant. Architecture firms often continue using outdated software to avoid the costs associated with updating systems, which can lead to long-term inefficiencies. By focusing on students, this research explores the potential challenges and necessities of maintaining currency in digital tools within the architectural profession, as these systems must eventually be updated to remain functional in a connected world.

This study tracked the students' journey through several design assignments. Throughout the course, two cohorts (2021 and 2022) completed 3 design assignments (see Table 3.2). Each assignment lasted for a duration of two weeks. The assignments were structured to include intermediary and final feedback sessions, encouraging a cyclical learning process of application, reflection, and refinement and eventually potential for reformulation processes. Within the scope of the class, students were given theoretical sessions and hands-on exercises that were deliberately kept separate from the three assignments used for data collection. Reflecting on prior iterations of this course, where assignments were shorter (one week) and relied heavily on students' prior knowledge, this study's extended task durations and structured feedback mechanisms to foster more information retrieval (Dissaux & Jancart, 2022).

The course was held weekly through a 4-hour class divided into four sections (see Figure 3.3). The first hour was dedicated to feedbacks on previous week's work, the second to a presentation about theoretical aspects of computational design, the third hour to hands-on exercises using worked examples unrelated to the design tasks and finally the fourth hour was dedicated to in-class work on the design task where students could communicate in person with each other as well as the the assistant, the teacher, and student monitors. Student monitors, who had previously taken the course before 2021 and were proficient in the parametric software Grasshopper©, played a supportive role. They were instructed to assist only upon student request to foster independent problem-solving. Additionally, to ensure continuous support, the monitors maintained an online conversation thread open for queries outside class hours, utilizing a group chat on the Facebook© messenger app.

The mixed-methods data collection strategy encompassed bi-weekly questionnaires aimed at gauging students' evolving perceptions and competencies before and after each task. Complementing these quantitative measures, semi-structured interviews at the end of the semester offered deeper qualitative insights into their design experiences. Furthermore, students' weekly presentations, totaling 42 across the course, served as both a progress tracking mechanism and a feedback conduit, enhancing the pedagogical value of the course by fostering a dynamic environment of self-assessment and peer critique, in line with the self-regulated learning principles emphasized in the literature (Abbasi et al., 2018).

Table 3.2: *Assignments descriptions*

Year	n°	Assignment
2021	1	**Pedestrian bridge**: This involves several considerations to ensure its functionality and safety. The bridge should be designed at an appropriate height to accommodate boats passing underneath. Additionally, it should accommodate the flow of both pedestrians and cyclists. Moreover, the presence of an obstacle necessitates a non-rectilinear bridge design.
	2	**Pavilions**: There are seven pavilions to be created each based on a main pavilion typology that serves as a theater. The proportions of closed, covered, and open spaces are predetermined. Furthermore, each pavilion has specific functions assigned to it, requiring careful planning and design to meet their respective purposes.
	3	**Highrise**: The building should consist of more than 20 stories and incorporate commercial, office, and residential spaces. It must also adhere to the designated building footprint. Additionally, the design should consider factors such as views and sun exposure to optimize the building's overall performance.
2022	1	**Pavilion for hikers**: Creation of a pavilion for hikers with adaptability in mind to comply with any type of path intersection. The design should also consider the importance of natural light to enhance the hikers' experience and create a pleasant environment within the pavilion.
	2	**Exploratory art piece**: The only constraint is that the final output must be a PNG file with specified dimensions. This allows for creative freedom and exploration in designing a visually engaging and expressive art piece and also an opportunity to explore tool affordances.
	3	**Multifunctional building**: Create a structure with less than 20 stories. The building should incorporate commercial, office, and residential spaces while respecting the designated building footprint. Additionally, the design should prioritize factors such as views and sun exposure to optimize the building's functionality and user experience.

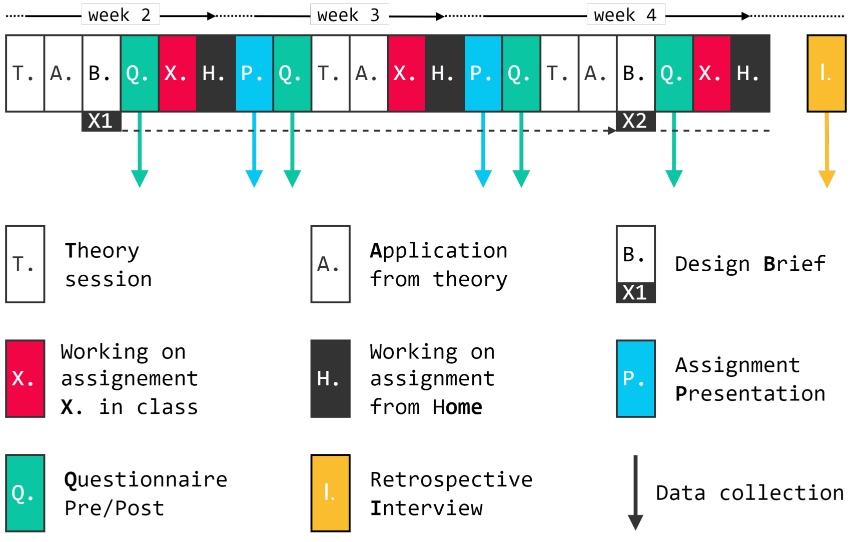


Figure 3.3: *Sample assignment organization.*

3.2.1.1 Quantitative approach to collecting data : survey

Surveys, recognized as a fundamental method for researching information behavior, facilitate the systematic collection of objective, anonymous data. This method is instrumental in identifying patterns, thereby enabling a comprehensive analysis of information-seeking behaviors (Julien et al., 2011).

In the context of Interactive Information Retrieval (IIR), surveys provide a benchmark for assessing the applicability of IIR principles within the conceptual framework, especially concerning creative tasks. The work of Urgo et al. (2020), which incorporates the knowledge dimension, exemplifies the utility of pre- and post-task questionnaires. A widely adopted research design involves the utilization of pre- and post-task questionnaires to evaluate how the task at hand influences search behaviors, as well as how the content of the information accessed may alter initial search strategies (D. Kelly et al., 2015; Urgo et al., 2020). In this study, the focus is on investigating the impact of IIR on the design process. The questionnaires are designed to capture participants' perceptions of task difficulty, types of information, and the sources from which this information is obtained.

Compared to other surveys in IIR, this research focuses on create tasks, measuring difficulty within a specific context through the use of pre- and post-search questionnaires. This methodology enables an examination of how these various measures interrelate, as well as their connection to search behavior. Furthermore, insights into how search strategies may be hindered are revealed by observing the differences between pre- and post-task responses.

To ensure comprehensive participation and mitigate potential apprehensions, surveys were administered online during class sessions. This approach combines the benefits of real-time support for any survey-related inquiries with the convenience and comfort of digital submission, less intimidating than in-person surveys (Campbell, 2017). The first pre/post task questionnaire followed a typical structure of pre/post task research in IIR. The goal was to collect quantitative information on the sources and the type of knowledge students would retrieve to complete their assignments and confront it with their evaluation of effort.

The questionnaire design adheres to established pre/post-task research conventions in IIR, aiming to quantitatively document the types and sources of knowledge students utilize in their design assignments. Scheduling the pre-task surveys immediately after the assignment distribution and conducting the post-task surveys at the beginning of subsequent sessions ensures a continuous reflection on the information retrieval experience throughout the design activity. This process resulted in three pre-task and six post-task surveys, designed to gauge both knowledge-related challenges and information sourcing patterns.

To ensure students were comfortable with the survey format and the concept of knowledge types, the questionnaires were introduced one week before the study commenced, using a sample assignment as a primer. This preparatory measure was taken to ensure that students were well-versed in the structure and goals of the survey, enhancing the reliability of their responses and facilitating data collection during the actual study period.

Utilizing a Likert scale, the pre-task surveys comprised five questions targeting perceived task difficulty and the necessity for various knowledge types (factual, procedural, conceptual). These survey components are detailed in Table 3.3.

Table 3.3: *Questions asked in the pre/post questionnaires right after students received the assignments, and after one and two weeks of working.*

Q#	Interest	Pre-task questionnaire	Post-task questionnaire
Q1	Task Difficulty	How difficult do you expect the task to be?	How difficult was it?
Q2	Tool Difficulty	How difficult do you expect the tool to be?	How difficult was using the tool?
Q3	Factual Knowledge	How inclined are you to look for factual knowledge?	What is the effort put into searching for factual knowledge?
Q4	Procedural Knowledge	How inclined are you to look for procedural knowledge?	What is the effort put into searching for procedural knowledge?
Q5	Conceptual Knowledge	How inclined are you to look for conceptual knowledge?	What is the effort put into searching for conceptual knowledge?

The second part of the pre-post task questionnaire was designed to probe into the students' information source preferences, tracking their anticipated versus actual use of various resources. By offering a selection of predefined options, ranging from direct human interactions (teacher, monitor, group) to digital and printed mediums (forums, images, videos, course materials, books) (see Table 3.4), this questionnaire is also indicative of the correlations between the effort invested in the class and the type of information sourced (Li et al., 2022). This approach facilitated a nuanced understanding of the students' information-seeking behaviors and the knowledge types most associated with each source, particularly highlighting the role of videos in conveying procedural knowledge.

Table 3.4: *Sources proposed in the questionnaire and their abbreviations.*

People			Internet				Printed
Teacher	Monitor	Group	Forum	Image	Video	Course	Book
Tc	Mn	Gr	Fr	Im	Vd	Cr	Bk

Each source falls into one of three categories: people (direct interaction), internet, or printed material, each with different applicable modalities. Direct communication with people offers numerous possibilities compared to the internet, which primarily relies on text-prompted searches. Course material includes theoretical content and worked examples presented in class, and all are available online. Course material is specifically multimodal as it usually displays text and images as well as videos. Books are based on index search and potentially the librarian (people) or an internet prior internet search to identify and locate the book. Additionally, provision was made for unforeseen sources of information by including an option for participants to manually specify any other sources not initially considered in the survey. The source is also indicative of the type of knowledge they retrieve. For example videos are often associated with procedural knowledge (Li et al., 2022) but nuances had to be discovered through further investigations.

To ensure clarity and precision in responses, students received guidance on interpreting the options. One common indication was emphasizing the primary source of information over secondary recommendations (e.g., choosing 'monitor' if the monitor suggests a video). This clarification was crucial in addressing initial confusions, especially regarding the categorization of internet sources. The survey refined its focus on the nature of the information rather than the intermediaries used to find it, streamlining the categorization process and enhancing the accuracy of the collected data.

By categorizing information sources and providing explicit instructions, this segment of the questionnaire not only captured the diverse information-seeking strategies employed by students but also laid the groundwork for subsequent analyses that would explore the impact of these strategies on their design processes.

3.2.1.2 Qualitative approach to collect data

The qualitative aspect of this research is based on the principles of protocol analysis, a method extensively utilized in design studies. This approach is particularly aligned with the theoretical frameworks of Function-Behavior-Structure (FBS) and Concept-Knowledge (CK), where it has been effectively applied to understand the complexities of design thinking and knowledge application.

Protocol analysis is an empirical, observational research method widely used in design research. It involves recording the sequence of designers' behaviors over time, including verbalizations, sketches, and audio-visual materials (Akin & Lin, 1995; Newell, 1991). Initiated by Eastman (1969), protocol analysis has since become a vital tool for investigating the cognitive processes of designers. Despite ongoing debates regarding its effectiveness, it is widely recognized among scholars for its unique capability to provide direct insights into designers' thought processes. By effectively bridging observable behaviors with internal cognitive functions, protocol analysis offers a robust framework for understanding complex design activities (Akin & Lin, 1995; Craig, 2001; Cross et al., 1996; Cross, 2001; Eastman, 1969; Lloyd et al., 1995; Newell, 1991; Suwa & Tversky, 1997).

In design, two primary approaches are recognized for analyzing design activities: process-oriented and content-oriented analysis. The process-oriented approach focuses on the process aspects of design, including problem-solving actions and strategies closely tied to the design process itself. Conversely, content-oriented analysis focuses on the elements designers engage with, such as what they observe, engage in, and contemplate, offering insights into the cognitive aspects of design beyond merely the process structure. However, the adequacy of verbal data in capturing the full scope of the content-oriented process is subject to debate, suggesting that it may not fully encapsulate the depth of designers' cognitive engagement with their work (Coley et al., 2007; Dorst & Dijkhuis, 1995; H. Jiang & Yen, 2009).

The methodological discussion on protocol analysis highlights the complex interplay between verbalization and the visual-spatial dimensions of design, reflecting on the limitations of verbal reports to fully encapsulate design intricacies (Ericsson & Simon, 1993; Lawson, 1998; Lawson, 2012). Schön (1983) emphasized the intertwined nature of verbal and non-verbal elements in the "language of designing," while Akin and Lin (1995) introduced the concept of dual-mode design thinking, merging verbal-conceptual and visual-graphic elements. This research employs a dual approach, integrating process-oriented interviews to gather verbal insights and content-oriented logs to capture visual data, thereby ensuring a subsequent holistic analysis that embraces both verbal and non-verbal dimensions of design cognition and activity. Consequently, these considerations imply specific requirements for data collection.

Interviews

Most studies employing protocol analysis utilize concurrent methods, often incorporating think-aloud protocols during the experiments (Hay et al., 2017; H. Jiang & Yen, 2009) (see Figure 3.4 and 3.5). Concurrently, protocols are often very limited in time. However, due to the longitudinal nature of this study, employing concurrent protocol would have been impractical. The extended length of the design process, combined with logistical challenges in recording students' design activities outside of class, made think-aloud and concurrent approaches unfeasible. Additionally, implementing concurrent coding in class was logistically challenging due to the number of students involved. Consequently, a retrospective approach with interviews was selected.

Table1: Taxonomy of Design Protocol Publications

Verbalization type \ Participants		Individual	Group	Both Individual & Group	Total
Report while task	Concurrent	Think aloud 65	Conversational 37	6	108
Report after task	Retrospective	12	0	0	12
	Introspective	4	0	0	4
Combined Protocols		6	0	0	6
Others		2	2	0	4
Total		89	39	6	134

Figure 3.4: *Repartition of design protocol publication in 2009 (Jiang & Yen, 2009).*

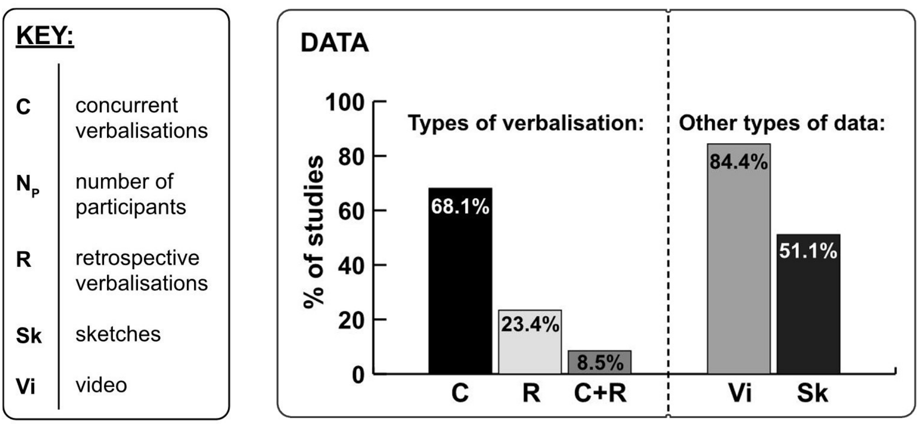


Figure 3.5: *Repartition of design protocol publication in 2017 (Hay et al., 2017). The chart shows a slight increase in the proportion of retrospective protocols 8 years later. The use of videos serves both as a base for conducting videos to alleviate the risk of selective recall and as content for analysis. Additionally sketches are often employed but do not necessarily convey information retrieval during design.*

Gero and Tang's (2001) work demonstrates that both concurrent and retrospective protocols can produce comparable results in studies that examine the process-oriented aspects of design activity. Interviews were conducted in the week following the last assignment. Ericson and Simon (Ericsson & Simon, 1993) advocate for conducting interviews immediately after the activity to capture fresh insights. They also recommend that the activity be of short duration to facilitate this immediacy. Due to the longitudinal nature of the study, adhering strictly to those guidelines proved impractical. Therefore, the decision was made to conduct semi-structured interviews, utilizing a blend of deductive and inductive coding techniques. This method aligns with the protocol detailed in Table 3.5, providing flexibility to adapt to the evolving context of the research while ensuring systematic data collection and analysis (Kaufmann & Singly, 2016). The interviews followed the guide in table 3.5

Table 3.5: *Semi-structure interview guide.*

Questions	Follow-up
Describe your design process	How has it evolved during the course ?
Describe your relationship with information	What information did you rely on
What are the differences with the design process when parametric tools are not involved	On what kind of information do you rely on when you don't use parametric tools

Logs

The log approach is found to be effective in eliciting specific elements of design activity amenable to verbal articulation (Pedgley, 2007) and is a good substitute to the more popular retrospective protocol which can be prone to selective recall particularly in the context of a class (Angulo, 2007; Suwa & Tversky, 1997). There have been studies employing design logs in education studies but unlike this study, they are most often focused on logging as part of the learning activity (Babapour et al., 2014; Robertson, 2011; Y. Zhang et al., 2020). Furthermore the diaries permit long-term analysis which allows for information search activity, as shorter time constraints might induce behaviors based primarily on prior knowledge (Dissaux & Jancart, 2022; Yu & Gero, 2015).

A presentation template was provided to the students with each day represented on a slide allowing them to easily document their daily progress (see Figure 3.6). Students were also asked to present their diaries each week, which helped to hold them accountable for their work. All presentations were recorded in case of a misunderstanding regarding the content (e.g. a screenshot of design activity that turns out to be taken out of a video tutorial).

With this dataset in place the diaries underwent a marking process. This marking aimed to unveil ways in which information might have influenced the students' decisions and actions as well as how these students in turn were influenced by the information at their disposal. This process involved a qualitative assessment of the diary content seeking to uncover the interplay between knowledge

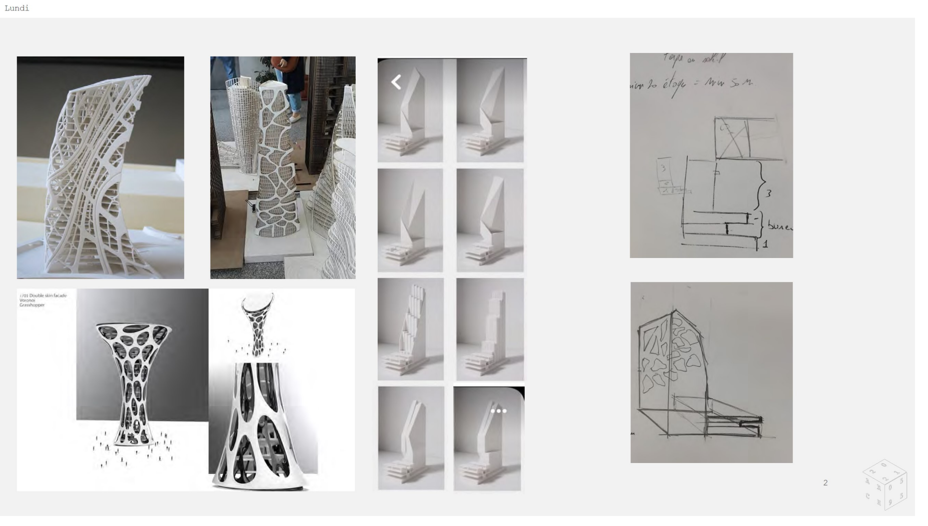


Figure 3.6: *The presentation slide offers a snapshot of the group's process. In the top left corner, the day of the week is displayed in French ("lundi"). The group has collected images for reference and created sketches. During the presentation, the group disclosed that their sketches were made after reviewing the retrieved images. They also revealed that the bottom-left image on the slide is actually the thumbnail of a video tutorial.*

retrieval design processes and tool usage within the specific context of this study. Eventually the content displayed in the presentations is compared to the final result

3.2.2 Data analysis

The mixed-method approach incorporates coding as a foundational analytical method, supported by protocol analysis. However, given the nature of protocol analysis and the conceptual framework developed in this study, it is crucial that the coding methods align with the study's conceptual framework and research objectives rather than adhering to predetermined codes (Saldaña, 2013). Consequently, hypothesis coding is employed, marking a departure from protocol analysis. The provisional coding scheme is developed based on the formulated hypotheses and subsequent research questions, enabling a structured yet adaptable analysis of the data.

This strategy ensures that data analysis is consistently anchored in the study's theoretical underpinnings. Hypothesis Coding differs from Protocol Coding in that the former's set of codes is usually developed within the research itself, while the latter's set of codes has been developed by other researchers (Saldaña, 2013). Hypothesis coding allows for the testing of hypotheses derived from the conceptual framework through the application of a researcher-generated, predetermined list of codes. These codes are devised based on theories or predictions about the findings before data collection or analysis, enabling the verification of assumptions (Bernard, 2018).

Additionally, coding offers a means to quantify qualitative data for comparison. This involves creating codes and themes qualitatively, then counting the number of times they occur in the text or visual data. This quantification enables researchers to compare quantitative findings with qualitative insights. Conversely, quantitative data may be qualified; for example, factor analysis from scale data may lead to the creation of factors or themes for comparison with qualitative data themes (Creswell, 2014).

The coding framework provides a preliminary and detailed analysis of aspects of the data pertinent to the research interest specifically the nature of information, and its impact on the different processes in relation to effort. The established codes aim to elucidate the research questions, grounded in the conceptual framework encompassing the nature of information, cognitive processes, and cognitive load.

The nature of information is delineated by its type, as described in the Information Interaction Research (IIR): Factual Information I^F, Procedural Information I^P, and Conceptual Information I^C. Additionally, this study introduces a distinction in information based on its category, categorizing it as either Design-oriented I_D or Tool-oriented I_T (see Table 3.6). This distinction is critical for understanding the specific uses and applications of information within the design process. Furthermore, the source of information plays a pivotal role in determining the modality of queries, eventually informing on the impact of recommender systems.

Table 3.6: *Different Abbreviations for information qualification.*

$I_{D,T}^{F,P,C}$			
Information Category		Information Type	
I_D	Design related information	I^F	Factual information
I_T	Tool related information	I^P	Procedural information
		I^C	Conceptual information

The survey directly captures the nature of information by inquiring into the sample's perspectives. It examines information categories through the measure of perceived difficulty, whether design-related or tool-related. The survey also asks about the type of knowledge used and the specific information sources consulted. codes are explicit to systematically categorize responses, ensuring that each piece of data could be analyzed in relation to the broader themes of the study. Cognitive processes are not part of the survey however the differential analysis between pre and post-task data unveils the underlying cognitive adjustments and learning processes triggered by the task, offering insights into how cognitive processes evolve in response to design challenges. The survey allows for the collection of data prior to the task, capturing students' perceived affordances and preferences regarding information investment based on anticipated task difficulty. This pre-task perception provides crucial insight into their initial information retrieval and design strategy.

The post-task questionnaire further elucidates the disparity between perceived affordances and the actual processes employed, enabling the identification of significant points of interest. It reveals potential disconnects between the initial strategies envisioned by the students and the strategies they actually implemented, as discussed in Section 2.3. This dual approach, combining pre- and post-task assessments, is instrumental in uncovering the impact of cognitive load on design effort and in highlighting how students adapt their strategies in response to encountered difficulties. However it must account for lack of digital literacy as the students might not be self aware of discontinuities as described by Claeys (2023)

Similarly, for the interviews, the same set of codes is applied to the content across three dimensions pertinent to each interviewee's responses. This approach enables a detailed exploration of knowledge expansion in design and tools through information retrieval, as well as the definition of the resulting affordance space. Informations sources appear as abbreviations (see Table 3.4)

The interviews gathers all 3 dimensions of the information's nature through interpretation and its coding. For example "tutorials" are often mentioned and are interpreted through investigative iterations as procedural tool-related information I_T^P that are found on the internet as videos. Design processes, including information retrieval are reported in view of inspiration (see Table 3.7).

Themes extracted are then examined in terms of design process and reported by considering the information nature and in view of the established model. This approach provides a comprehensive examination of the strategies architects use during the information retrieval process, detailing the cognitive steps from the initial definition of search inputs to the final selection of information as a potential factor for reformulation. A sample can be seen in Table 3.8.

Table 3.7: *Processes in relation to inspiration. The structure S is at the center of the model and that is where information retrieval starts however as seen in inspiration the search input definition can be the result of a more nuanced approach including formulation and synthesis.*

Inspiration Phase	Cognitive Process
Keyword Definition	Formulation F $\rightarrow$ Be
	Synthesis Be $\rightarrow$ S
	Query S $\rightarrow$ I_D,I_T
Search Strategy (Behavior)	Recommendation 1 I_D ↻
	Recommendation 1 I_T ↻
	Recommendation 2 $I_D \leftrightarrow I_T$
Selection	Selection I_D, I_T $\rightarrow$ in
	Knowledge process in $\rightarrow$ S

Table 3.8: *Coding example of an episode during an interview*

id	Ts	Sp	Tr	Coding	Theme
110	10:11	B	There were a lot of websites but still, videos, it's always better.	Videos are always better showing a tendency towards procedural knowledge I^P #search I_D I_T #Vd	Information sources and strategies
111		B	For example, there are groups that relied heavily on a tutorial and started from that tutorial.	Claiming other students start from a tutorial #query #search I^P #Gr	
112		B	For us, that wasn't the idea at all; it was really about finding the answer to our problem, but not relying on the entire algorithm.	Again explicit regarding looking for factual solutions to their problems using videos I^F #search I_D I_T #Vd	

The analysis of the logs uses the established coding scheme to categorize content, and information retrieval activities. By organizing the content into two main categories, design-related and tool-related, a consistent analytical perspective is maintained. Adopting a retrospective approach naturally allows for conceptualizing design processes at a more abstract level. Referring to Table 3.7 and the established conceptual framework, keyword definition initiates a transition from the design domain (D) to the information domain (I), where search activities take place (D $\rightarrow$ I). The selection process then represents a return to the design domain D (I $\rightarrow$ D).

Considering the logs focus on content it is possible to identify the category of information reported directly as it is the only explicit data reported. The distinct information categories define the extension of each knowledge domain independently as sub-systems of affordance K_D and K_T. The content displayed in the logs are mostly structures S resulting of design iterations. The structure S stands out as the central figure situated at the intersection of design knowledge K_D and tool knowledge K_T (S $= S = K_D \cap K_T$). If a representation exists, it means the corresponding structure exists within the intersection of K_D and K_T. It is important to note that a specific structure might exist to highlight a gap in knowledge (see Figure). For instance a sketch might represent the structure that needs to be transposed from one tool (sketching or K_{T2}) to another tool K_{T2}. However different stimuli that have not been integrated can also appear as part of the exploration process, providing indication of abandonment. These stimuli can also be interpreted as external structures yet to be transposed.

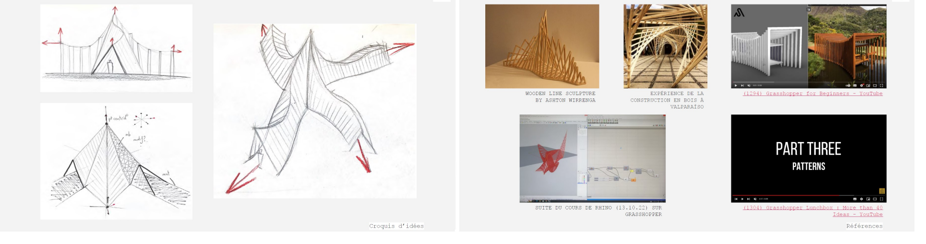


Figure 3.7: *In this example, the sketches (left picture) are structures at the intersection of design knowledge and tool knowledge if the tool considered is sketching however it does not exist within* K_T *if parametric tool is considered. It will dictate the subsequent definition of search inputs to expand parametric* K_T *(right picture), and be able to transpose that structure to the parametric tool.*

For the analysis, $K_D \rightarrow$ and $\leftarrow K_T$ are defined as extension of knowledge subject to all potential search biases (arrows point towards the central structure S). The extension of knowledge is considered here as serving the initial design structure S and results into a reformulation process. Alternatively $\rightarrow K_D$ and $K_T \leftarrow$

represent cases when there is no initial design structure besides a search query or when the initial structure is disregarded in favor of unforeseen encountered information ($\mathrm{K}_D \nrightarrow \mathrm{K}_D$ and $\mathrm{K}_T \nleftarrow \mathrm{K}_T$). In that case reformulation 1 can only be concerned with the search definition as there is no initial visual representation.

This nuanced approach to coding is designed to systematically explore the complex interactions between design thinking, tool usage, and information retrieval. By adopting a higher level of abstraction and encompassing the three distinct data sets while considering variations in information retrieval strategies, it facilitates a comprehensive analysis. Additionally, a quantitative view of the data is obtained by grouping occurrences of intersections between design and tool knowledge experiences for each assignment and across the semester. This second-cycle approach, similar to pattern coding, provides a broader perspective by grouping these intersections, enabling the identification and categorization of emerging patterns and themes. This structured process aids in forming a robust analytical framework.

This unified coding framework is developed to categorize the data collected from the survey, interviews, and logs, serving as a cornerstone for the concurrent mixed-methods approach. This consistency in coding across different data sources facilitates a cross-analysis, allowing for a comprehensive understanding of the design and information retrieval processes under study (see Figure 3.9).

Eventually cognitive load theory and underlying assumptions will be used in the discussion as it is proposed to explain the different behaviors that are reported. When analyzing effort, the focus is on identifying the challenges faced at different stages of the inspiration process, with the aim of determining whether cognitive load impacts information retrieval and thus the design process. Consequently, the role of metacognitive strategies in potentially mitigating these challenges is taken into account.

Given the uniform application of the coding framework across these diverse data sources, the analysis was able to rely on a higher-level conceptual understanding of design and tool knowledge expansions. This unified coding approach not only facilitated a granular examination of individual data points but also enabled a holistic comparative analysis, linking the initial stages of development to the final outcomes and shedding light on the developmental trajectory and impact of information retrieval on design processes.

Table 3.9: *Data Analysis*

Data Collection - Code dimension	Nature of Information	Design Processes	Effort
Surveys	Explicit count approach	Pre/Post difference comparing initial strategy to actual search behavior	Explicit evaluation
Interviews	Implicit/explicit recall through verbalization	Recall through verbalization	Recall through verbalization
Logs	Extracted from visual content	Extracted from visual content	Extracted from visual content

3.2.3 Summary

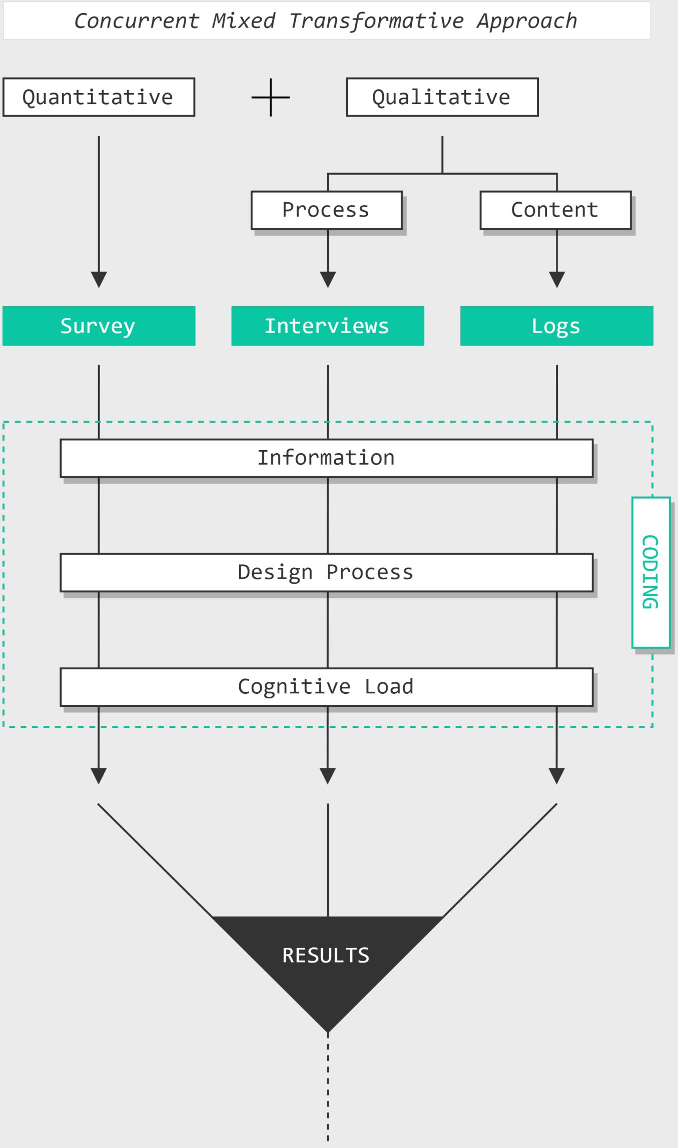
This chapter delineates the research methodology and design, focusing on the impact of information retrieval on the architectural design process. The aim is to explore the dynamic interplay between design, tool usage, and information retrieval within the architectural domain, guided by a conceptual framework that integrates Information Retrieval, Design and inspiration theory, Tools, Search Systems, Affordance, and Cognitive Load.

The research setting involved an elective class titled "Introduction to Computational Design" at the University of Liège, engaging Master of Architecture students with no prior exposure to parametric design. This setting provided a fertile ground for examining the self-regulated learning aspects in architecture and the adaptability required in navigating contemporary digital tools.

Employing a concurrent transformative mixed methods approach, the study integrates quantitative and qualitative research methodologies to dissect the complex effects of information retrieval on architectural design. This multifaceted investigative approach enables an in-depth analysis of cognitive processes, information characteristics, and the methodologies deployed in expanding design and tool knowledge. Such a comprehensive exploration aims to enhance understanding of architects' strategies for navigating extensive information landscapes, thereby informing and evolving design methodologies.

Accordingly, data collection combined quantitative and qualitative approaches to offer a comprehensive view of the students' engagement with information retrieval and design processes. Bi-weekly questionnaires were used to track students' evolving perceptions and competencies, while semi-structured interviews and student logs offered deeper insights into their design experiences. This methodological approach facilitated an exploration of the students' journey through design assignments, capturing their perceptions, strategies, and the cognitive processes at play.

The data analysis employed a unified coding framework developed to categorize data from surveys, interviews, and logs, utilizing hypothesis coding as a common base for analysis across the mixed concurrent approach and protocol analysis. By examining the nature of information, design processes (including inspiration and effort), and cognitive aspects, the analysis sought to uncover the dynamic relationship between design reformulation and information retrieval, emphasizing the role of procedural knowledge, cognitive load management, and the digital ecosystem in contemporary architectural design activity.


Concurrent Mixed Transformative Approach
Quantitative
Qualitative
Process
Content
Survey
Interviews
Logs
Information
Design Process
Cognitive Load
CODING
RESULTS

4 Results

This chapter presents the findings from the various data collection methods employed in the study, showcasing how information retrieval impacts architectural design processes. The results are systematically divided into sections based on different data sources: surveys, interviews, and logs, each providing unique insights into the facets of information utilization in architecture.

The survey results are detailed first, breaking down the types of information architects seek, their sources, and the difficulties they encounter. This section quantitatively analyzes how specific information types and sources influence architectural design and the perceived challenges faced by architecture students in accessing necessary information.

Interviews offer deeper qualitative insights into the processes of information retrieval as an integral part of architectural design. Key themes are extracted and explored. These interviews illustrate the subjective experiences of designers and their interactive dynamics with information tools.

Log data provides an objective lens, examining the patterns in tool usage and knowledge expansion. This includes how designers' knowledge of tools and design concepts evolve over time, leading to shifts in design strategies.

The chapter concludes with a detailed interpretation of these findings through the lens of the developed model. This comprehensive analysis not only highlights the current state of information retrieval in architecture but also sets the stage for discussing its broader implications in the next chapter.

4.1 Survey

The survey results are presented with a focus on the nature of the information, including its type (factual, procedural, or conceptual), its source, and its category, represented here as the effort invested in design and the tool itself. The data is analyzed both individually and collectively for each assignment in the years 2021 and 2022. It's worth noting that the results may vary between assignments due to their unique nature. Additionally, as students progress through the semester and reach the third assignment, they accumulate a broader pool of tool knowledge. This analysis provides insights into the evolving preferences and consistencies in information-seeking behavior over the two years in the classroom context.

4.1.1 Information Type

In evaluating the effort invested towards different types of information, as shown in Figure 4.1, the data reveals the effort across both years of collection. It's important to note that students may invest effort in searching for conceptual information but end up finding and selecting procedural information even though that perception might be biased. This discrepancy indicates a deeper cognitive processing beyond the initial search intent. All charts present the results from the pre-task reference next to those from the post-task questionnaire for comparison.

For factual information, initially, students expected to invest a moderate amount of effort into I^F, as shown in the Pre-task questionnaire. After one week (Part 1), the effort invested appears to have slightly decreased. By the end of the second week (Part 2), the effort invested in I^F remained consistent with the effort reported after one week.

For procedural information the anticipated effort was slightly higher than for factual information in the Pre-task predictions. Effort invested in searching procedural information peaks the second week (Part 2) could indicate that the practical aspects of the task became more pressing as students began to implement their ideas but then tapered off as they overcame initial procedural challenges.

Regarding conceptual information, students anticipated similar effort according to the Pre-task questionnaire. The actual effort invested in I^C decreased significantly after one week (Part 1), indicating that students possibly engaged less with understanding concepts than they expected to. By the end of the second week (Part 2), the effort reported slightly increased but still remained well below the anticipated effort level, a deeper engagement with the conceptual elements of the assignments over time but also suggesting a overestimated engagement with conceptual understanding throughout the assignment.

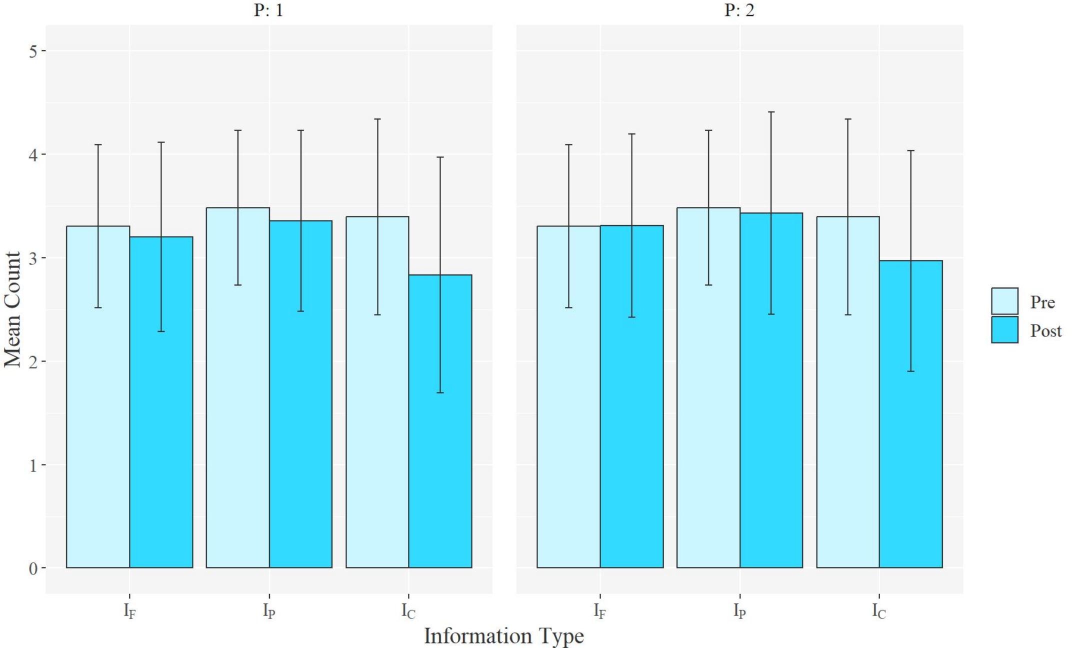


Figure 4.1: *The charts present the average investment into each information type (I^F, I^P, and I^C). Pre- and post-task data are positioned side by side for comparison. These data are shown for both weeks, labeled as Part (P) 1 and 2, encompassing inputs from all participating students across both years.*

These observations reflect a nuanced relationship between students' intentions and their actual engagement with different types of knowledge throughout the design process. The variations in cognitive effort invested in I^F, I^P, and I^C over time highlight the evolving nature of cognitive engagement in architectural design education, where initial expectations may not always align with actual cognitive demands as students progress through their assignments.

Overall, the variations are marginal in pre-task questionnaires. However, post-task questionnaires show that procedural information receives slightly more preference than conceptual knowledge, suggesting that students may tend to overestimate their engagement with conceptual knowledge. This is possibly due to the challenging nature of conceptual information, which may not yield immediate practical results for create tasks like design. While overall variations remain marginal at this stage, error bars show a wide range of profiles among students, particularly in relation to individual assignments.

Analyzing the data on a yearly basis reveals more contrast for the year 2021 (see Figure 4.2). In 2021 students showed smaller investment into conceptual knowledge yet there is little to no difference between factual and procedural knowledge. In 2022 results show less contrast between the anticipated and actual efforts (see Figure 4.3). Again the differences are still marginal as they must account for diversity for each assignment.

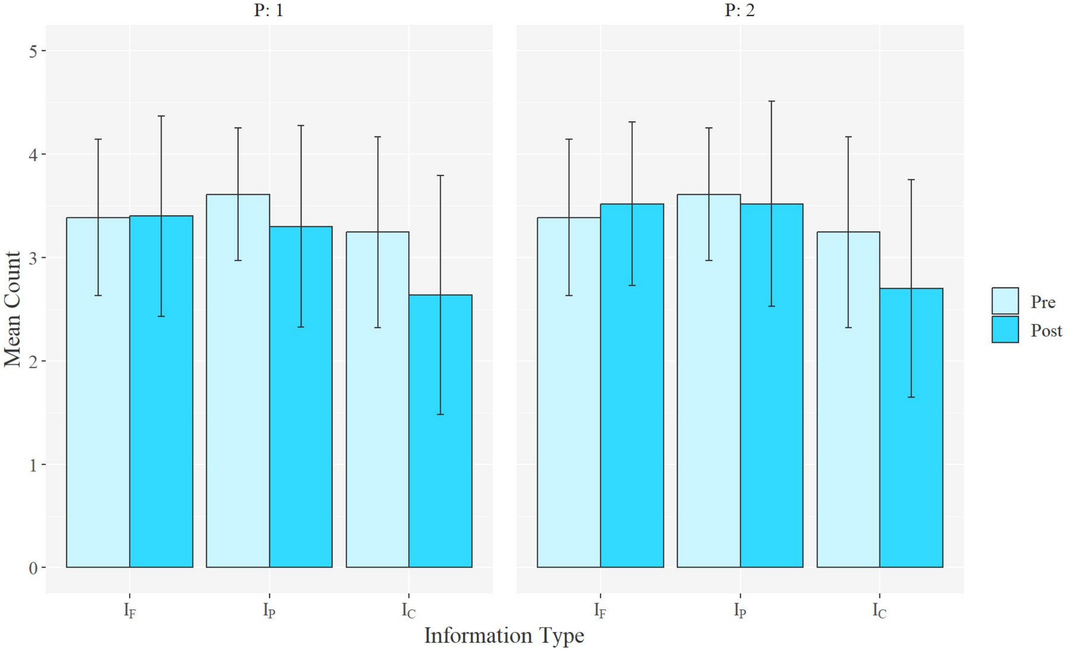


Figure 4.2: *Average cognitive investment into each information type ratings per part (P) for 2021.*

When examining each assignment individually for 2021, a slight preference for procedural knowledge only emerged by the third assignment, hinting at the growing importance of practical, step-by-step knowledge as the complexity of the tasks increased (see Figure 4.4). This could reflect a natural progression in the design learning process, where students move from searching for factual information to applying procedural information as they become more engaged more engaged with the tool. Furthermore it might hint at an adaptation in search strategy as procedural information might prove less cognitively demanding. Overestimation for the cognitive investment into conceptual information is systematically displayed here.

In contrast, the 2022 cohort showed less contrast between the anticipated and

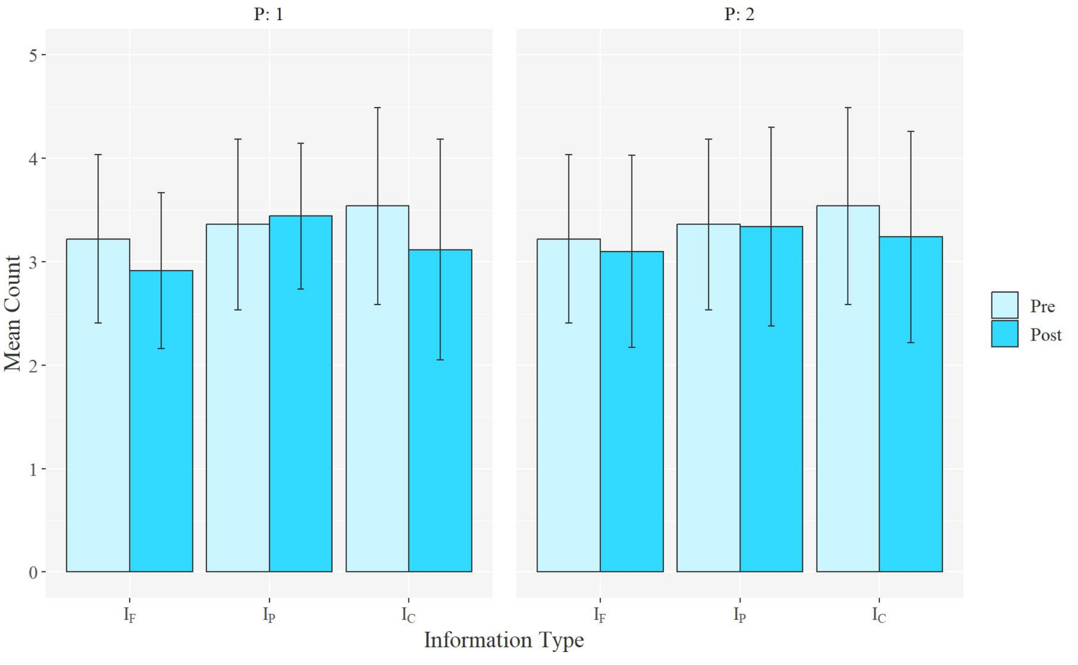


Figure 4.3: *Average cognitive investment into each information type ratings per part (P) for 2022.*

actual efforts, with a notable exception in the second assignment where the investment in conceptual knowledge exceeded expectations (see Figure 4.5). This outlier suggests that the nature of the second assignment in 2022 may have required a deeper conceptual understanding, prompting students to engage more intensively with conceptual information than they had predicted. Note that in 2022 following the first week of the second assignment, there was no post-task questionnaire due to a national holiday.

Across both years, the overall trend suggests an initial overestimation of the cognitive investment required for conceptual information, but the actual investment varies based on assignment specifics and the evolving competencies of students as they advance through the design process. While no significant differences stand out, students' engagement with various types of information remains fluid and is shaped by the specific demands of each assignment. The wide spread of the data indicates further lack of patterns but also suggests a total lack of frame in terms of adopting search strategies during the design process.

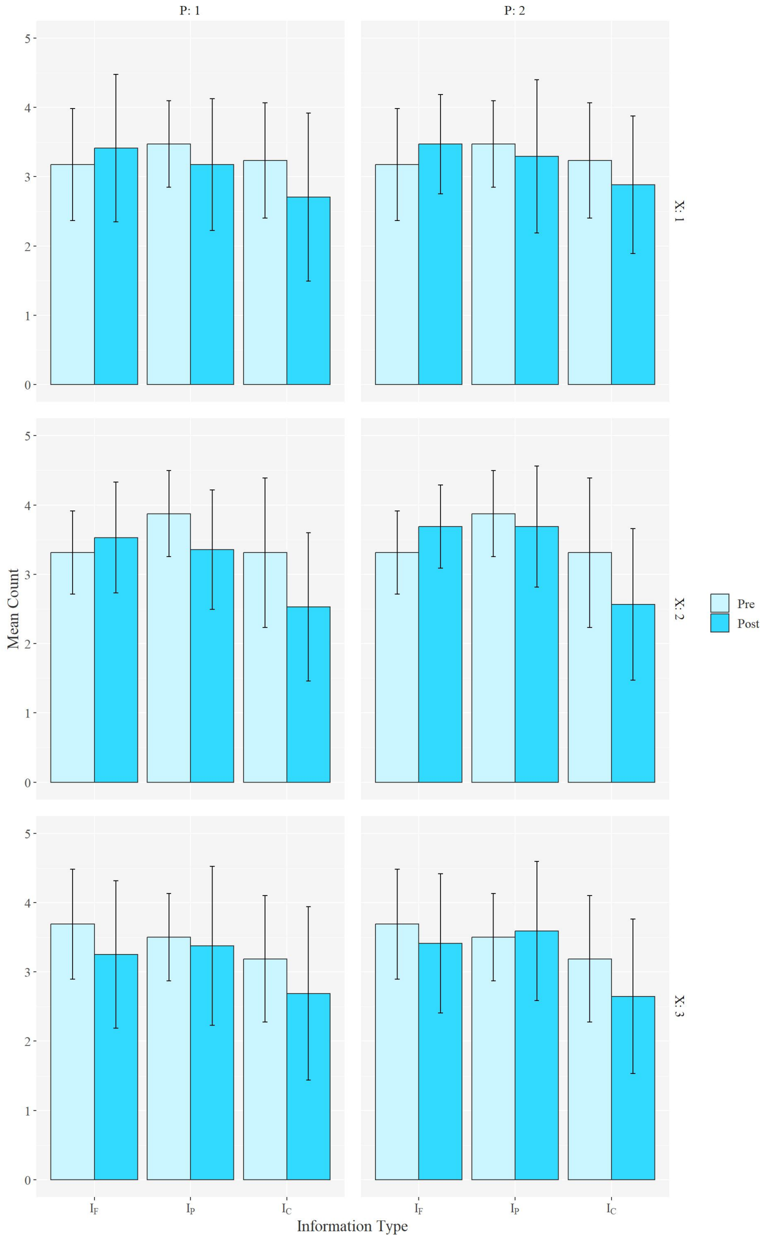


Figure 4.4: *Average cognitive investment into each information type ratings per part (P) and per assignement (X), for 2021.*

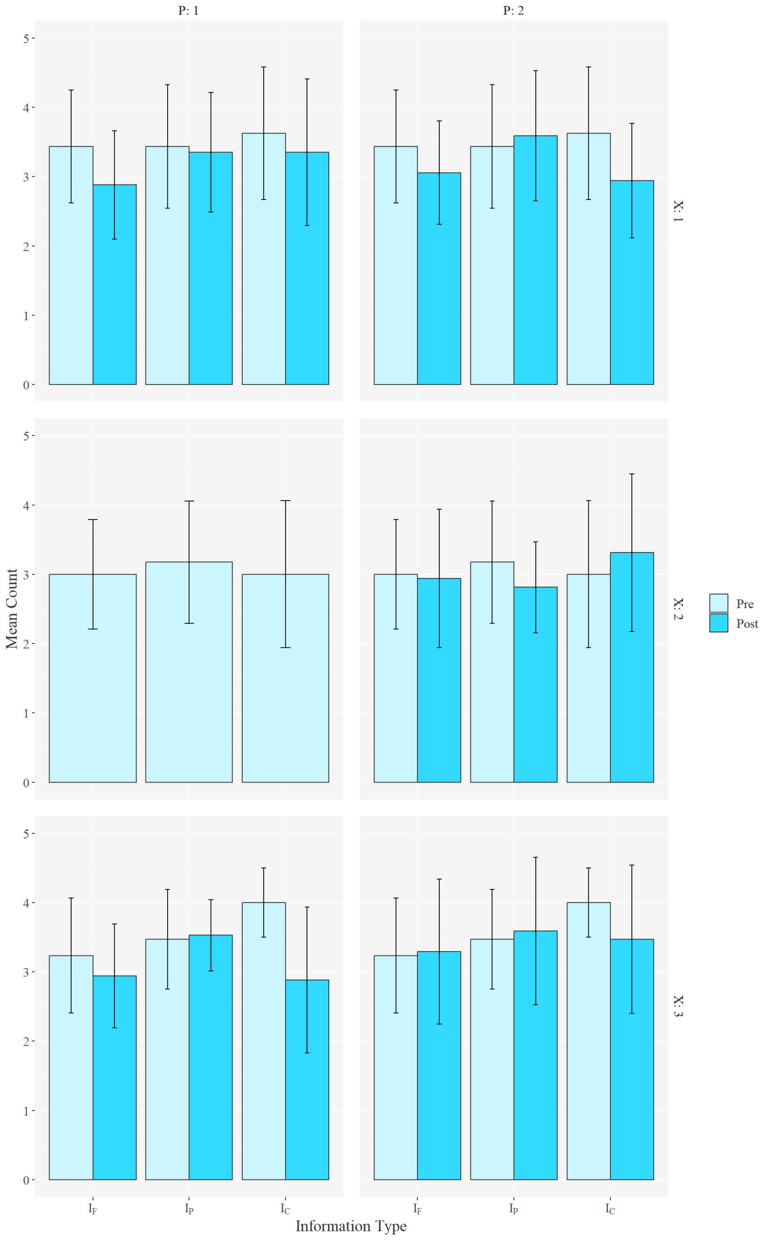


Figure 4.5: *Average cognitive investment into each information type ratings per part (P) and per assignement (X), for 2022.*

4.1.2 Information Source

In evaluating the sources of information, videos emerge as the most popular choice (see Figure 4.6). This preference for video could be attributed to the visual and demonstrative nature of videos.

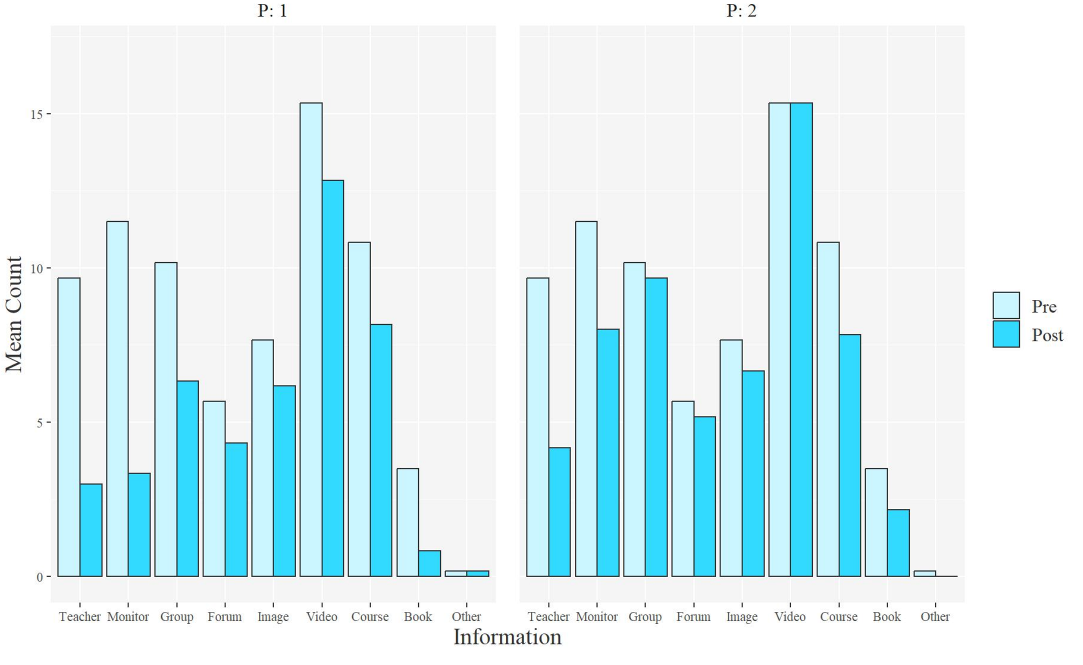


Figure 4.6: *Mean count between 2021 and 2022 of information sources used per part (P).*

Printed materials, such as books, appear to be almost non-existent as a source, which reflects the current digital learning trends and possibly the immediacy of accessing information online. Conversely, personal interactions as information sources, including assistance from professors and the group, seem to gain prominence in part 2 as project deadlines approach, serving perhaps as a "last resort." The rise in seeking personal assistance under time pressure supports the notion that complexity in design tasks may not necessarily increase, but the perception of complexity and urgency does as students approach their deadlines.

The reluctance to immediately ask questions may stem from the challenge of articulating problems without a solid grasp of the material. This is further compounded by the format of communication; students prefer face-to-face interactions, where they can use sketches and gestures, over written explanations in chats when monitors are not available.

Group work is another significant source of information, reflecting the collaborative nature of learning, especially among novices. However, the expected reliance on teachers and assistants did not materialize as strongly in practice. This could be due to a reluctance to reveal gaps in understanding to those evaluating their work, highlighting a potential barrier to seeking help in class environments.

Blogs, forums, and other textual sources were not heavily utilized, suggesting that navigating these platforms effectively may require a level of prior knowledge or familiarity that novice students do not possess similarly to their interaction with the monitors over the group chat. The low use of images contradicts previous research that emphasizes their popularity among architects. This could indicate a shift in information preference in the context of complex tool environments like Parametric Design Environments (PDEs).

Course materials remained a consistent source, likely due to their accessibility and the context in which they are introduced. Interestingly, an external person knowledgeable about the tool emerged as a source, which was not pre-identified in the survey categories. This points to the possibility that the categories provided were either sufficiently comprehensive or potentially lacking in detail.

More specifically, in 2021, the low use of images aligns with the low use of forums suggesting that students might have preferred more direct and interactive sources of information, such as monitors, who can provide immediate and personalized assistance (see Figure 4.7). Monitors being very popular could indicate their effectiveness in assisting students or a higher level of comfort among students in seeking help from them.

For the 2022 class, the growing preference for using images and the transition from relying on monitors to engaging in group work could indicate several developments (as illustrated in Figure 4.8). The increased utilization of images might be associated with the nature of the assignments, as observed in the analysis of knowledge types. The increased reliance on group work over monitors could point to a stronger group dynamic or a greater confidence among students in collaborative design. It could also suggest that the 2022 monitors may not have been as approachable or effective as those in 2021, leading students to turn to their peers instead.

It's also possible that the 2022 cohort had a different level of prior experience or familiarity with the subject matter, influencing their resource preferences. The increased reliance on conceptual information as images might reflect a more abstract or concept-driven approach to the assignments in that year. These results underscore the importance of considering the human element in educational settings. Changes in personnel, such as monitors, can potentially

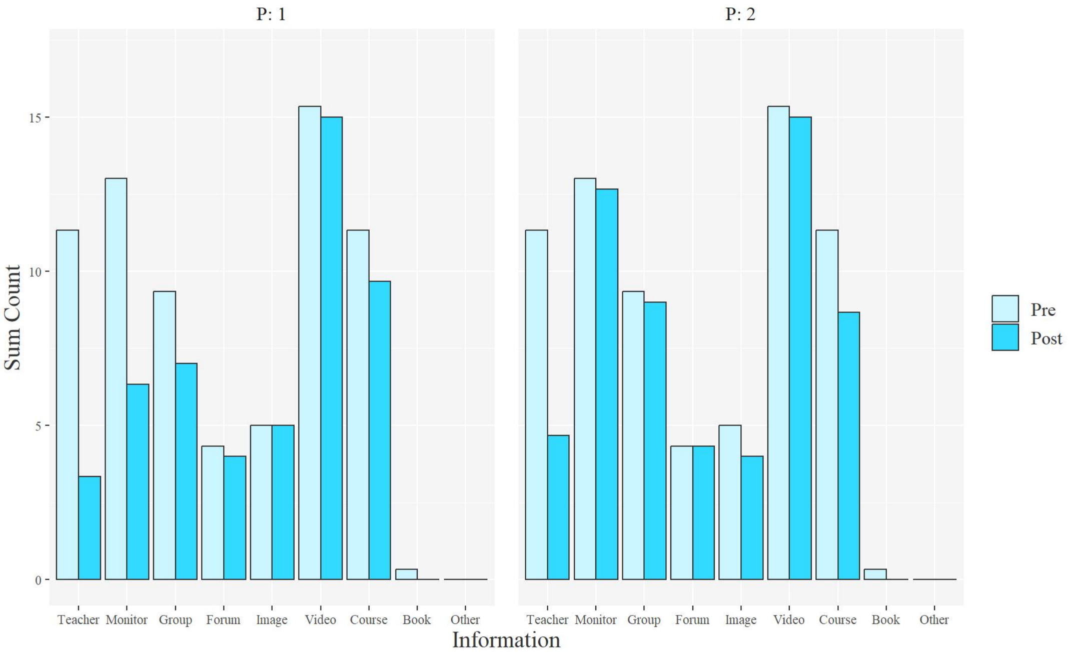


Figure 4.7: *Information source and modality preference for 2021.*

impact how students engage with information and each other.

Across the 3 assignements, 2021 saw a decrease in images as information source. Monitors as source is also decreasing a bit however one of the highest peak in videos appear for the last assignment suggesting students have learned to even more appreciate videos as sources despite their newly acquired knowledge suggesting developing cognitive strategies towards lesser effort. In 2022 there is seems to show some evolution towards more autonomy by the end of X3 with less reliance on referent people (see Figure 4.10. Additionally, 22X2 appears as an outlier again with a notable initial emphasis on images, which, towards the end, shifts back in favor of videos.

Overall, the results point to a need for improvements in facilitating autonomous learning and resource navigation for students. The findings also suggest that in the context of PDEs, traditional sources such as printed materials and static images may be less favored, whereas dynamic and interactive resources like videos become more crucial. This shift in source preference emphasizes the importance of adapting educational resources and support systems to better align with the tools and learning environments students encounter.

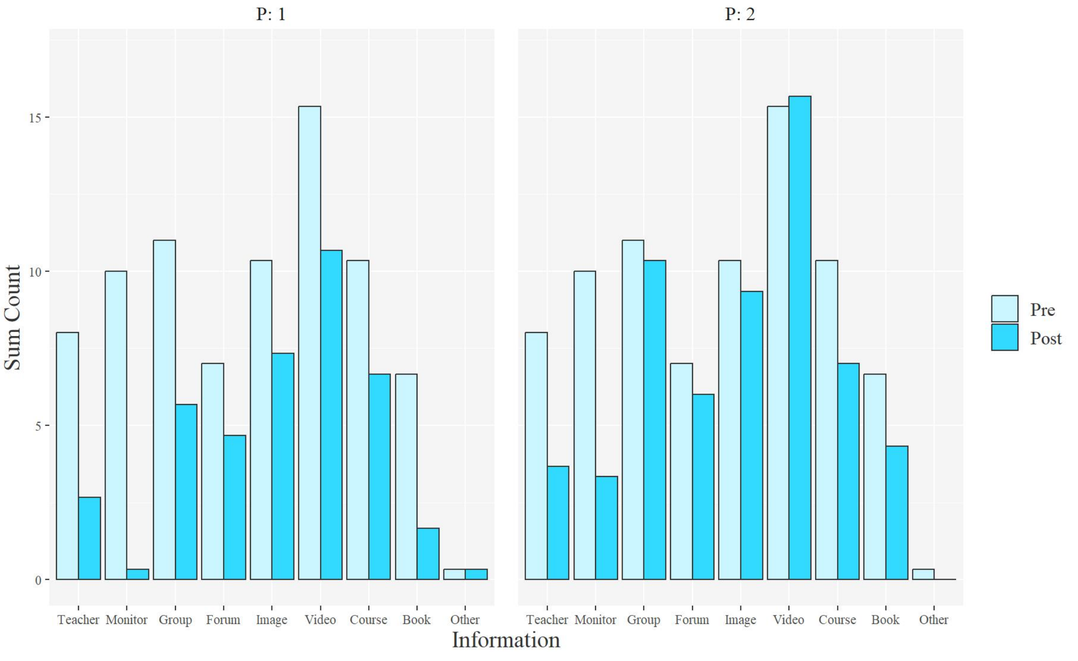


Figure 4.8: *Information source and modality preference for 2022.*

The observations across the three assignments for each class reveal interesting patterns of source utilization and search behaviors:

For 2021, there's a noted decrease in the use of images as an information source across assignments (see Figure 4.9). Additionally, even as students gain more knowledge, the reliance on videos increases, peaking in the last assignment. This suggests as stated earlier, a growing appreciation for video as source, which may offer more detailed procedural guidance or visual demonstrations that complement their learning.

In 2022, the data indicates a progression towards greater autonomy, particularly evident by the end of the third assignment (X3), with reduced reliance on reference people such as monitors and teachers (see Figure 4.10). This shift towards autonomy is a positive indicator of students' developing confidence and capability in self-directed learning within the PDE context. The second assignment (22X2) stands out as an anomaly, with a high initial expectation for the use of images, yet by the end, this expectation shifts in favor of videos, aligning with the overall trend towards dynamic learning resources.

These patterns underscore the evolving nature of students' engagement with different types of information sources over time and suggest a learning curve where students gradually discover and adapt their preferences for information sources that best support their design process within PDEs. The shift away from more traditional sources like printed materials and images towards more dynamic, interactive resources such as videos could reflect the complex nature of PDEs and possibly other complex digital tools that would benefit from step-by-step visual guidance.

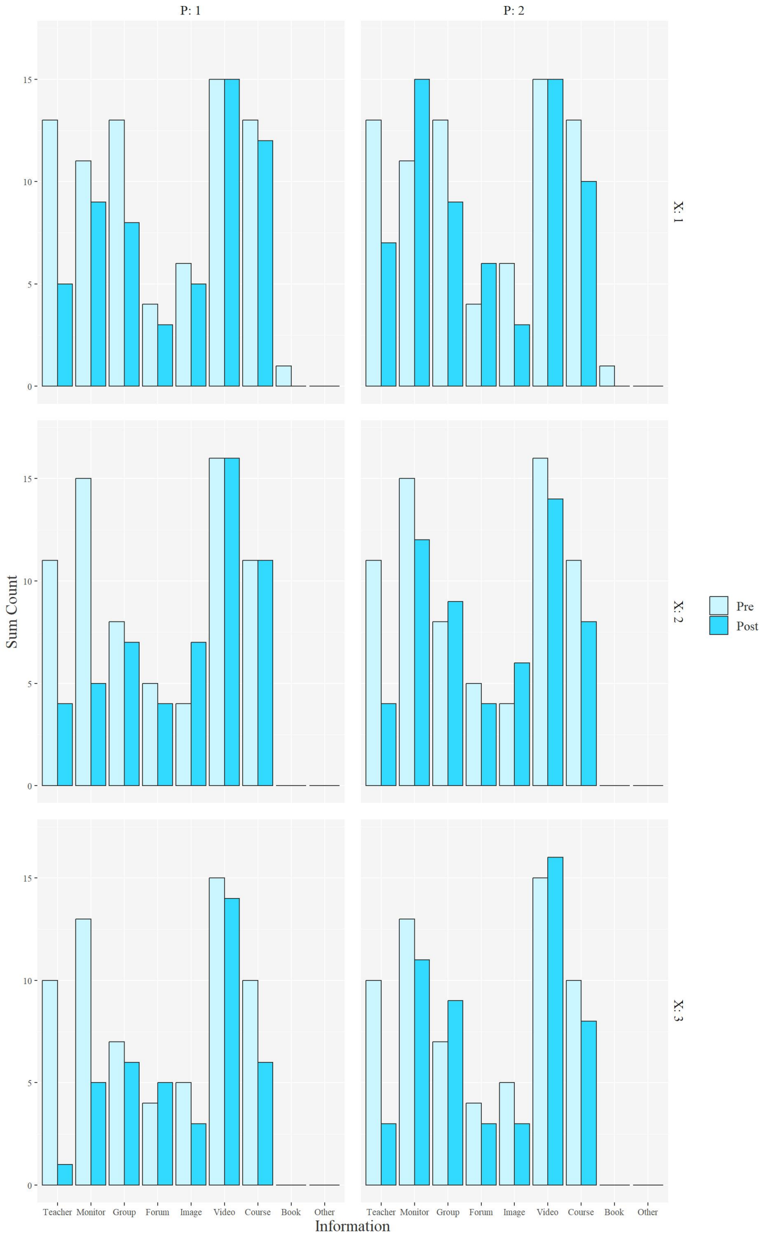


Figure 4.9: *Information source and modality preference, per part (P) and per assignement (X), for 2021.*

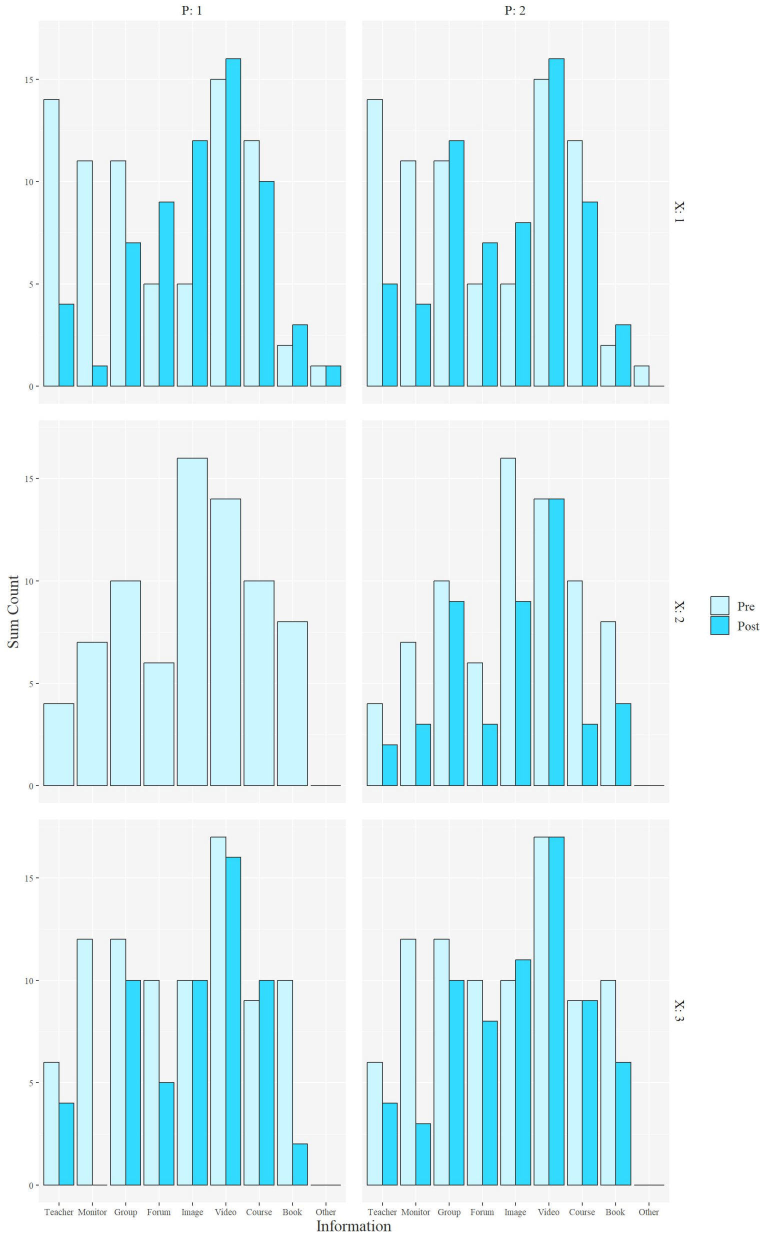


Figure 4.10: *Information source and modality preference, per part (P) and per assignement (X), for 2022.*

4.1.3 Comparison of Overall Task and Tool-Specific Difficulty

The charts provided here illustrate the distinction between the overall difficulty of the design task and the specific challenges associated with using the tool. The term "G-Diff" denotes the level of difficulty users encountered specifically with Grasshopper©. Overall the results indicate that while students might overestimate task difficulty initially, they may actually allocate more cognitive investment to the tool. The slight decrease in perceived difficulty could also result from increased familiarity with the tasks and tools over time. Nevertheless, the overall results show only marginal differences. The error bars reveal a wide spread in responses, indicating significant individual differences in students' experiences with design tasks and tools across assignments (see Figure 4.11).

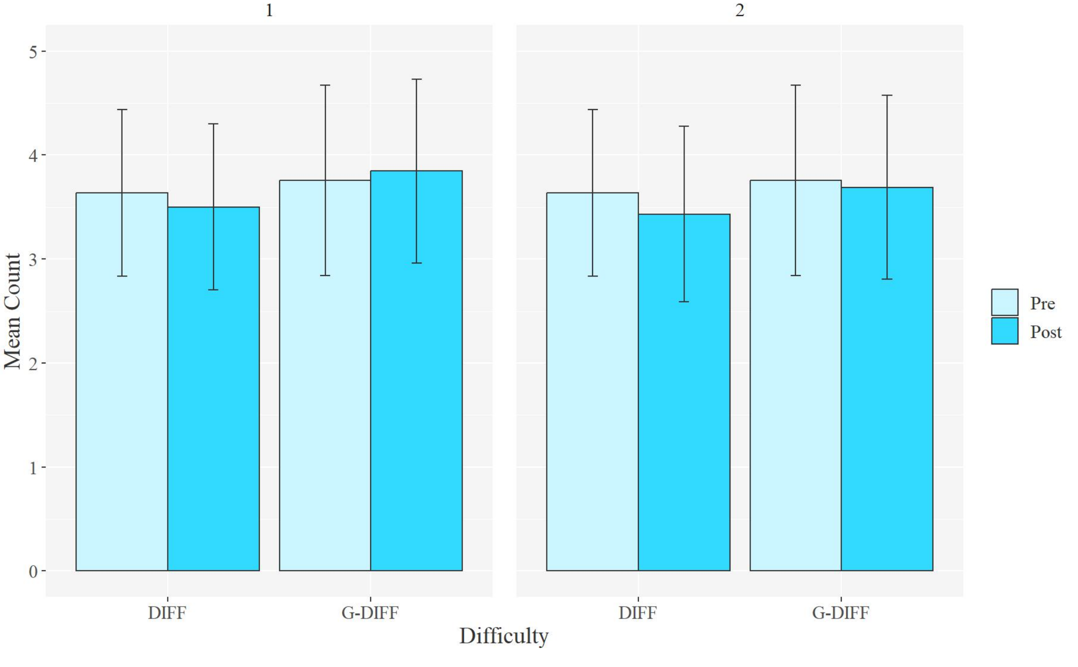


Figure 4.11: *Average difficulty ratings per part (P) for 2021 and 2022 (DIFF) compared to tool-related difficulty (G-DIFF).*

The equal weight given to tool-related difficulty and overall design difficulty underscores the importance of tool proficiency with the design process. It suggests that the tools are not merely instruments but integral components of the cognitive activity involved in designing. This could be due to the complexity of the tools, the novelty for the students, or the intrinsic demands of operating within PDEs. This suggests that, the perceived difficulty in design tasks is influenced by both the nature of the tasks and the cognitive demands of the tools used to execute them.

The similar levels of perceived difficulty reported in the figures (4.12 and 4.13) for both classes, and across the different assignments (4.14 and 4.15) acts as a manipulation check, verifying that the design tasks were indeed challenging and complex as intended, thus supporting the reliability of the study's design and execution. The anticipated complexity of design tasks, as confirmed by the results, supports the validity that the tools used in the design process are integral to the cognitive processes of design. This reinforces the argument that the cognitive load associated with tool usage should be considered an essential component of the design activity, alongside the design tasks themselves.

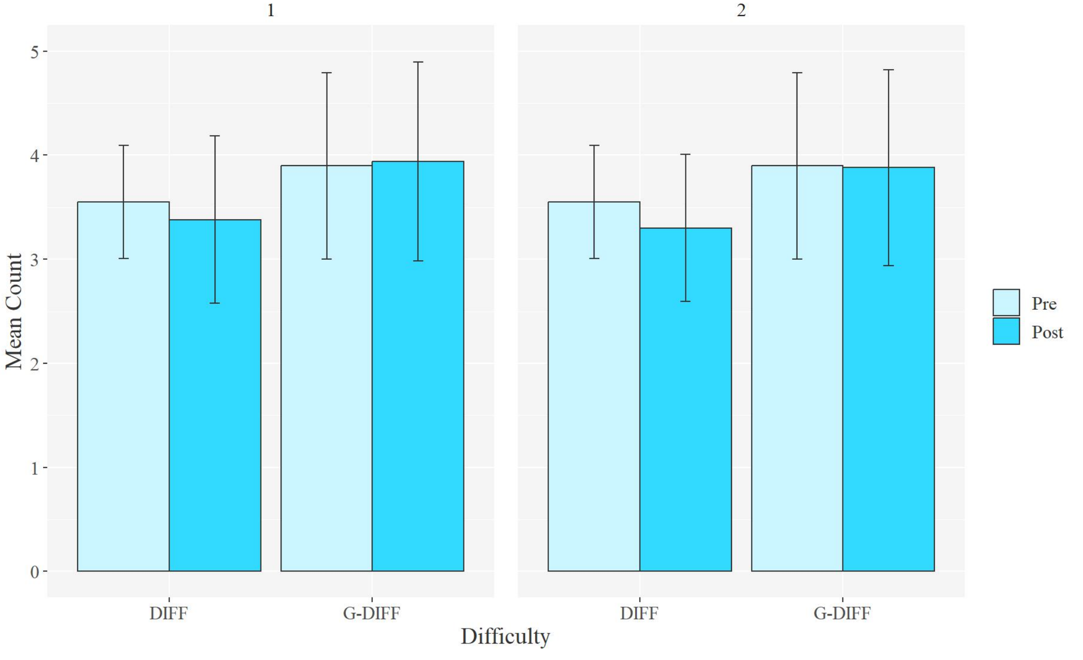


Figure 4.12: *Average difficulty ratings per part (P) for 2021 (DIFF) compared to tool-related difficulty (G-DIFF).*

In 2022, the perceived overall difficulty and the tool-specific difficulty ("G-Diff") appeared quite similar. In this period, students seemed to invest more effort into learning the tool (see Figure 4.13). Once again, results were consistent across assignments, with a slight outlier in Assignment 2, which displayed the lowest difficulty score (see Figure 4.15). Notably, this is the same assignment where students invested the most effort into conceptual information.

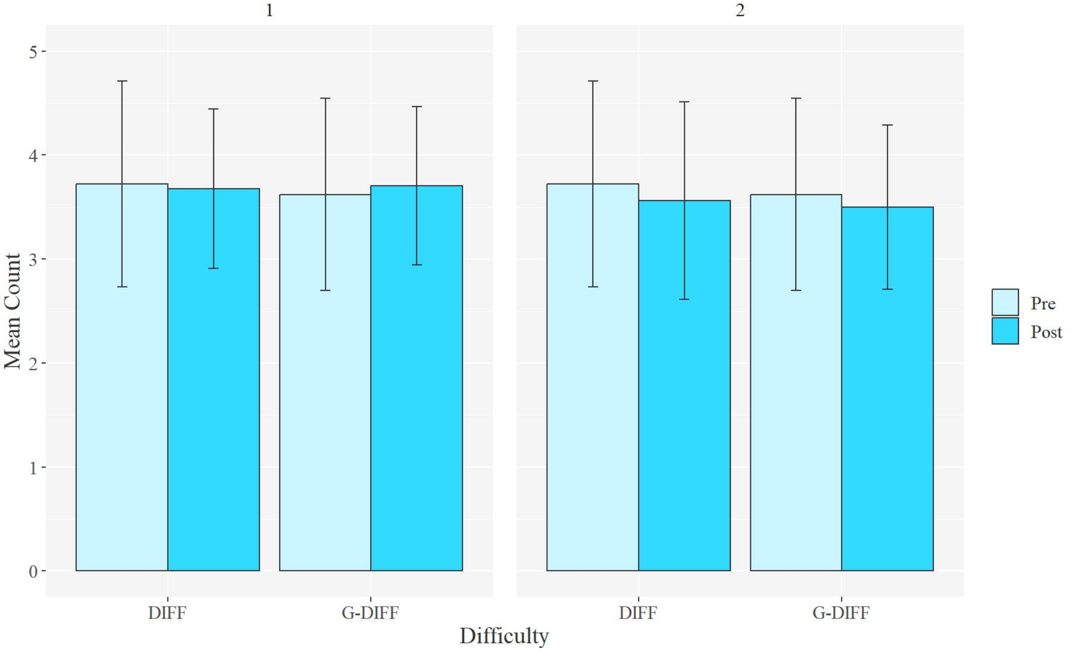


Figure 4.13: *Average difficulty ratings per part (P) for 2022 (DIFF) compared to tool-related difficulty (G-DIFF).*

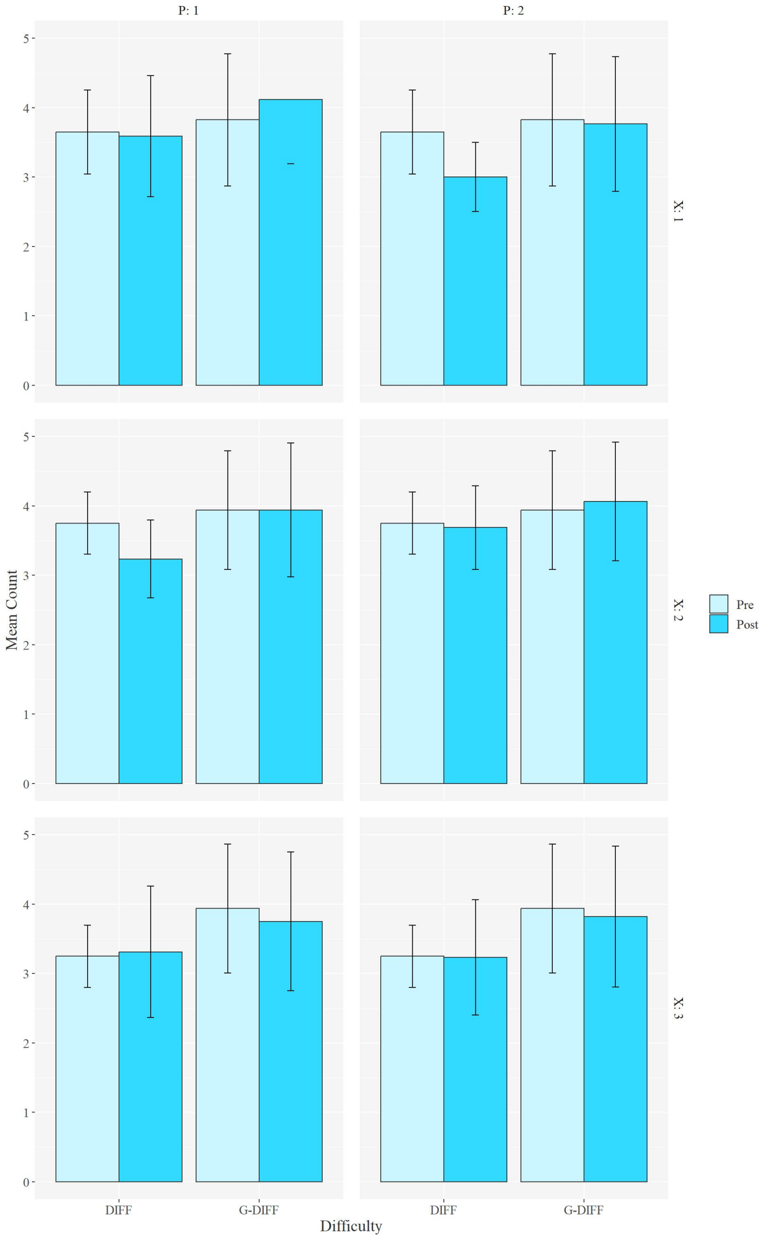


Figure 4.14: *Average difficulty ratings, per part (P) and per assignement (X), for 2021 (DIFF) compared to tool-related difficulty (G-DIFF).*

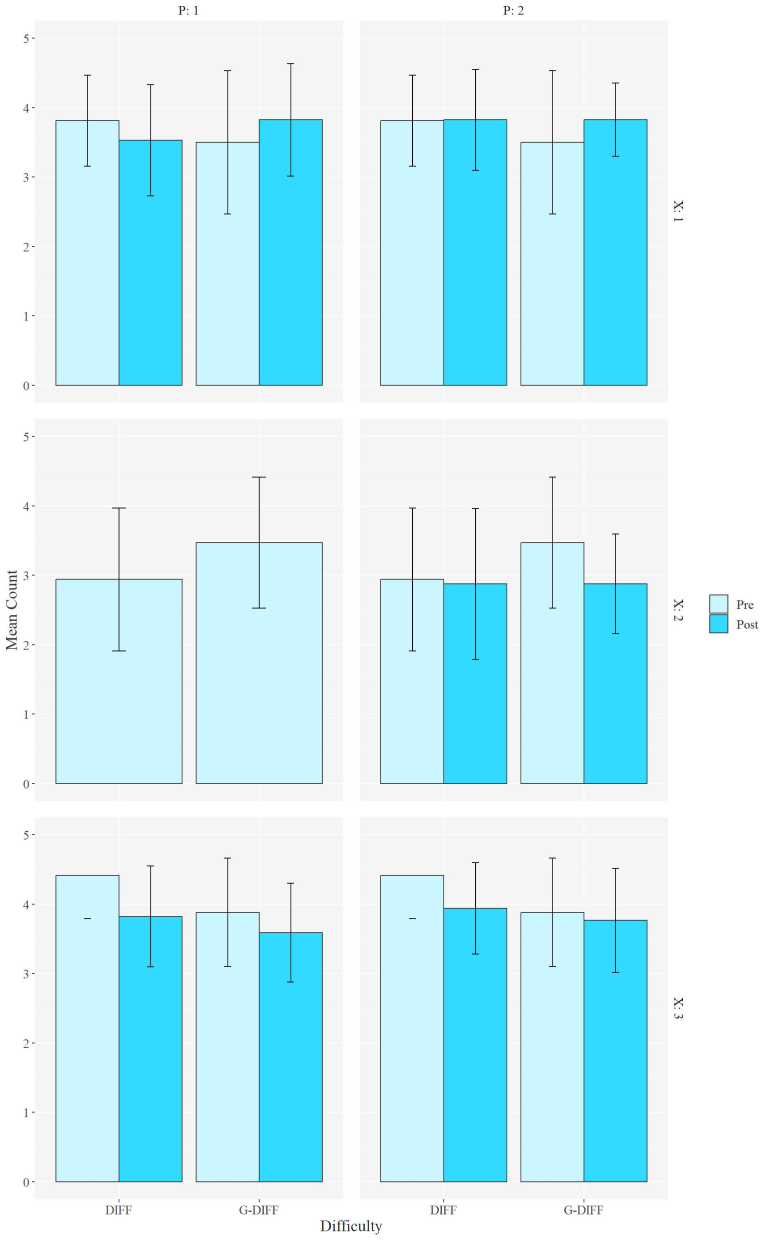


Figure 4.15: *Average difficulty ratings, per part (P) and per assignement (X), for 2022 (DIFF) compared to tool-related difficulty (G-DIFF).*

To conclude with the survey findings, the overall data presents a nuanced picture of student preferences and behaviors throughout the architectural design process. The surveys indicate a clear preference for procedural knowledge across most assignments, with an outlier in the second assignment of 2022 (22X2) suggesting an exception where conceptual information momentarily took precedence. This deviation highlights the variability in information needs depending on the specific requirements of each task.

Videos emerged as the dominant source of information, dwarfing images, which contrasts with initial expectations. This preference underscores the effectiveness of dynamic, visual content in conveying information The significance of video resources in the learning process points to the evolving landscape of educational resources, where traditional materials such as printed texts are becoming less central.

The cognitive load associated with design tools is revealed to be as substantial as the cognitive load involved in the design tasks themselves. This equivalence suggests that tool proficiency is not merely a supplementary skill but a core component of the design process in terms of cognitive investment.

Moreover, the survey results illuminate shifts in students' strategic approaches to information retrieval over time. Initially, students recognize the importance of conceptual information but as the design process unfolds, there seems to be a natural gravitation towards procedural and factual information. This shift might be attributed to the immediate applicability of procedural information in practical design tasks and the tangible nature of factual information in informing design decisions.

This dynamic interplay between anticipated and actual experiences encapsulates the essence of the design process. Students enter the design tasks armed with certain expectations about the difficulty, types, and sources of information they will need. Yet, these expectations are challenged and reshaped by their hands-on engagement with the design process, the real-world complexities encountered, and the adaptive strategies they deploy in response.

4.2 Interview insights on IR

This section explores insights from the interviews with architecture students, focusing on their design processes and how these processes have evolved throughout the course, particularly in relation to information retrieval. The emphasis is on identifying the impact of information retrieval on their architectural design activities. These interviews took place in the week immediately after the course concluded, with 29 out of 33 students participating throughout both years.

A predominant outcome from the interviews is the consistent integration of information retrieval into the students' design processes. All strategies necessarily lead to a tool supported structure as it's required for the class. Of course reliance on tool-related information (I_T) should be considered in the context of this class. It is expected that students will rely on information retrieval to navigate a new tool. During the interviews, it was observed that in situations where students possessed expertise over the tool, the impact of I_T on the design process was not readily apparent. This is because designers tend to rely on their prior knowledge of the tools they are accustomed to using. Several students mentioned that proficiency in familiar tools can mask the direct influence of information retrieval on their work, as they often depend on their accumulated knowledge and experience with these tools, rather than seeking new information. Conversely, similar concerns can be raised about strategies that do not incorporate I_T, suggesting a potential underestimation of tool knowledge's extent resulting in a limited affordance space for generativity. Nevertheless, regardless of the tool used, the process of information retrieval appears to be a common step in the design process among students (see Figure 4.16). This indicates a significant influence of IR on their design process, serving as a foundation check for this research. The insights reveal a complex interplay between digital tool proficiency, information retrieval strategies, and the architectural design process. This is illustrated in Figure 4.16 , which also shows the frequency of specific strategies employed by the students.

Figure 4.16 broadly illustrates the strategies used by the students, beginning with an initial structure from the design domain and an information category within the information domain. The diagram is organized between the initial requirements (R), represented by the assignment descriptions, and the Parametric Design Environment (PDE)-supported structure (S). Strategies range from A to H, with their sequences and occurrences observed during the interviews. While the sequence order is generally accurate, further nuances will be addressed later.

As anticipated, tool-related information retrieval (I_T) is prevalent in this course context, yet not ubiquitous. This suggests that some students may rely on acquired experience to navigate PDEs without requiring I_T, or they may use the

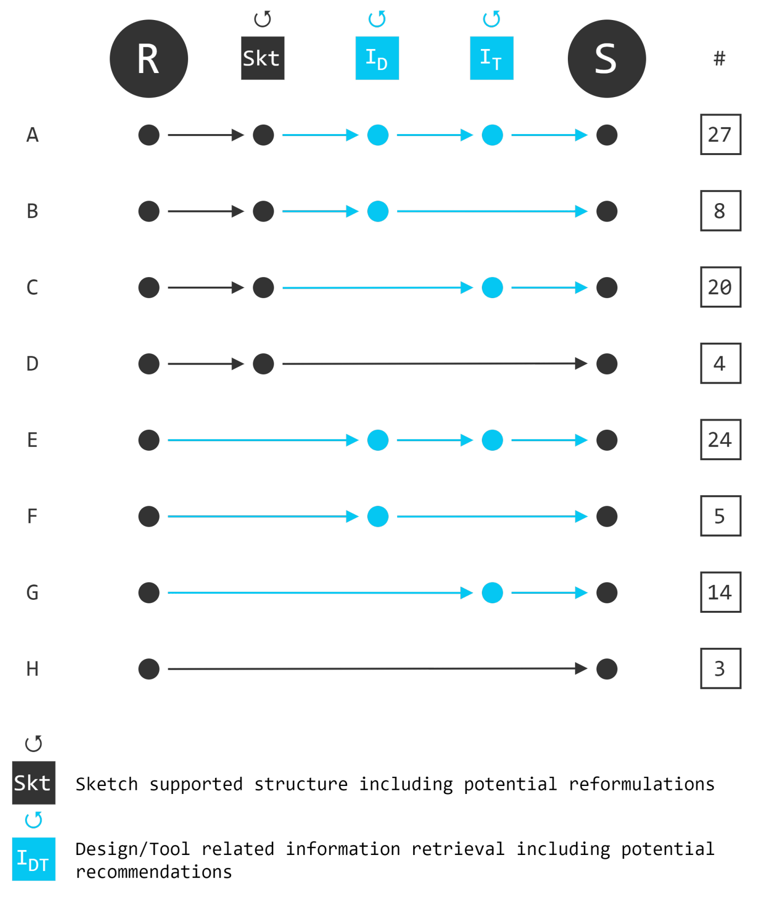


Figure 4.16: *Strategies from Requirements R to Grasshopper© supported structure S. The processes related to information retrieval appear in blue. The number of occurrences in interviews appear on the right.*

tool's user interface directly. Alternatively, they might lack the prior conceptual knowledge needed to formulate queries or simply omit mentioning their tool-related searches in interviews. Strategies A to C rely on a sketch as a foundation for subsequent search input definitions, with strategies A and B involving design-related information retrieval (I_D) to prompt reformulation of the initial structure before transposing to I_T. Strategy D uses the sketch but does not engage in information retrieval, possibly for the reasons outlined above.

Strategies E to G omit an initial sketch, using their query as their initial structure to proceed directly to information retrieval. It's important to note that students sometimes underestimated sketching's role in their design process and only mentioned it when prompted, implying that some occurrences in E, F, and G might actually belong to A, B, or C. Finally, some students reported bypassing information retrieval and heading straight to tool exploration within the PDE, often to “save time.”

In the absence of information retrieval, the design process inherently focuses on design domain specific processes such as formulation, synthesis, evaluation, analysis, and reformulation, consistent with the principles outlined in the Function-Behavior-Structure (FBS) ontology. The incorporation of information retrieval introduces a critical layer to the process: the inspiration phase, which encompasses keyword definition, search behavior, and ultimately, the selection of pertinent information. Each of these processes demands a significant cognitive effort, which can be mitigated through various strategies.

Regarding keyword definition, the effort towards formulation and synthesis is often directed at crafting search queries. Despite the potential for a rich exploration in this phase, the effort is frequently minimized, translating directly from assignment keywords to search input definition. Initially, the search strategy is primarily oriented towards retrieving I_D to identify relevant references, but it frequently shifts to I_T. A nuance emerges in that I_T retrieval can result either from unforeseen recommendations discovered during the search for I_D or from a deliberate, conscious retrieval process. The selection phase, typically characterized by recognition and curiosity, involves stimuli recognized as perceived affordance within the PDE. Additionally, the perceived affordance often hinges on the information source, with videos frequently offering a straightforward solution to the complexities introduced by PDEs.

The interview analysis reveals several key themes. Students often sidestep traditional initial formulation within the design domain in favor of directly sourcing references, indicating a shift towards a more information-driven design inception. Videos emerge as a favored medium, offering a blend of inspiration, procedural knowledge, and conceptual understanding, underscoring their pivotal role in the design process. The centrality of design tools highlights their significant influence on information retrieval strategies, demonstrating how tool features can shape information-seeking behaviors. Despite increasing tool proficiency, students' reliance on information retrieval intensifies, suggesting a deeper integration of information retrieval into their design practices. Surprisingly, social media plays a crucial role in passive information absorption and design inspiration, revealing an unexpected dimension of IR in architectural design. Overall these results collectively illustrate the evolving interplay between information retrieval, digital tool usage, and the architectural design process. In the subsequent analysis, nuances are highlighted through the constructed model by considering each individual process.

4.2.1 IR as substitue for initial formulation.

The initiation of the design process among architecture students reveals a significant preference towards the integration of information right from the start. This trend represents a departure from more conventional methods such as sketching, underscoring a growing dependency on information retrieval systems and their corresponding recommender algorithms in the early stages of design.

These systems streamline the reformulation process, suggesting a more passive approach to keyword refinement and conceptual development. The absence of problem framing accentuates information retrieval's crucial role in guiding students through the ambiguity of early design stages. Often, students begin with the assignment description, using it to effortlessly synthesize an initial structure S through keywords (see Figure 4.17). This approach may lead later in the process to a reformulation of the search input definition, but search systems simplify this effort by incorporating recommendations that automatically refine the search based on user interaction. For instance, selecting an image on a platform like Pinterest© leads to more images related to the previous clicked stimulus, acting as a proxy for reformulation without the necessity of engaging into synthetizing a new structure S. The reformulation might imply the correction or addition of keywords (R1) but might also touch upon previous issues such as the expected behavior Be via R2 or even the function F via R3 depending on how articulated the initial search input definition is and how much it's changed through information retrieval. Therefore recommendation appears as a black box reformulation process minimizing the cognitive effort required to reformulate a structure S.

> *22S02 (id20) : "In terms of research, it was really, for example, for the pavilion, we simply typed "parametric pavilion" and we browsed, whether it was on Google© Images or Pinterest© or some books."*

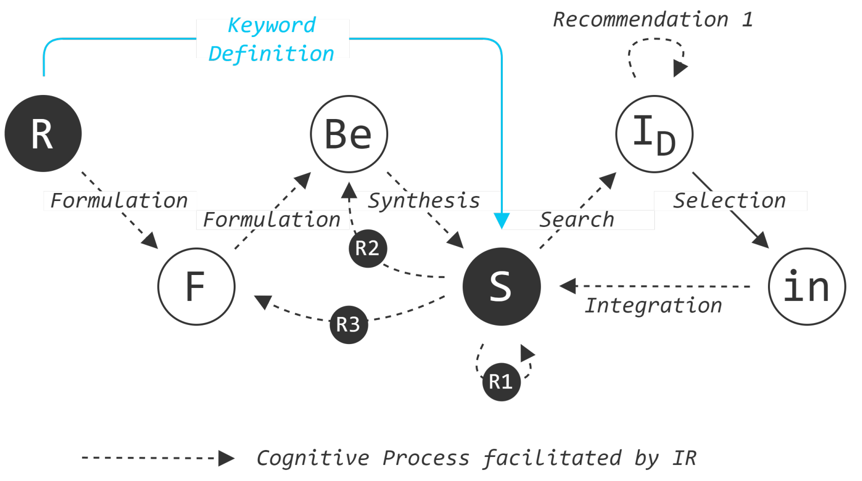


Figure 4.17: *Structure is a keyword definition based on requirements, and its reformulation is driven by recommendations alleviating the effort associated with formulation synthesis search and reformulation.*

When sketching is employed, it's often paired with information retrieval, indicating a blended approach to structure generation and refinement. This method shows that sketches can either be the result of an initial information-driven exploration or act as a basis for further information retrieval activities. In the latter case, the sketch provides a foundation for defining keywords to guide subsequent searches (see Figure 4.18). This requires reformulating the sketch into a search input, which could be biased due to a limited vocabulary, often leading to selections based on recognition and subsequent recommendations. Notably, in one particular instance, the sketch was reported to be text-based, which likely facilitated following text prompts.

> *22S10 (id135-142) : "We try a lot of things by hand and we also watch tutorials to see how we can (...) on that basis, we try to make sketches, but we push a bit more into sketches and everything and we see how we can really modify to our advantage and obtain something unique, original".*
>
> *21S07 (id51): "And when **Hidden** didn't come at one point, I had*

made more sketches to explain the design to him and to also convey my idea to him, just for that, at that time".

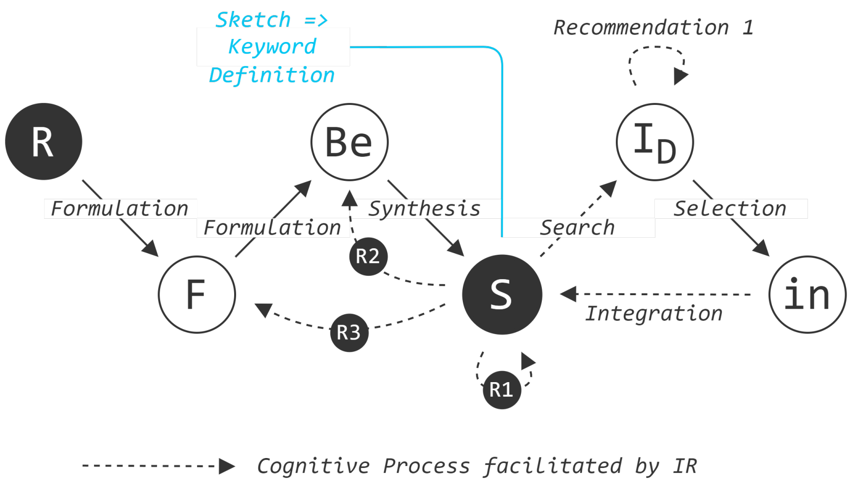


Figure 4.18: *The structure serving as search input is extracted from a previous sketch based structure.*

The integration of inspiration, plays a pivotal role in the reformulation processes that dictate function F and expected behavior Be and subsequently establish a foundational structure S that significantly informs the design direction. This process exemplifies the critical role of IR in facilitating an iterative exploration of design possibilities, demonstrating its integral position in today's design approach at least among students.

4.2.2 Impact of Assignment Description

The description of assignments serves as an important catalyst for initiating the design process, profoundly influencing the selection of keywords and the subsequent information retrieval strategies. Previously in Figure 4.17 the students tend to omit initial formulation and synthesis by going straight to information retrieval. In that case IR is seen as a way to start the project. Student will reiterate and potentially integrate sketches. However the strategy might be more solution oriented resulting in commitment to the resulting structure (see 4.19).

22S22 (id73-184): "At the beginning, we perhaps quickly turned to videos because we didn't yet have the basis to say, "ah yes, we'll do it like this or like that. (...) once we actually have the creative notion, I want to say, we try not to touch it anymore because in fact it's kind of the guiding thread of the entire project, and I feel like in Grasshopper©, what can be interesting is that this guiding thread, as they are only parameters, it will always be there, and it's just a volume that changes or a volumetry that changes or whatever, and so we can still tinker with it afterwards".

Assignments often stipulate specific requirements or themes that directly inform the initial set of keywords used by students. This predefined context facilitates a more directed search for relevant information, narrowing down the information landscape to those that are most closely related to the task at hand, but also the tool used, therefore reducing considerably analogical distance (see Figure 4.19). In addition those considerations should also incorporate the tool as it is implicitly part of the assignment.

22S03 (id158): "Because I think we all typed things like "abstract" or similar".

22S04 (id23): "So we go on Google©, we type in the keywords and see what we get".

The inclusion of tool-specific goals during the class introduces students to specialized vocabularies in their keyword definition, implicitly guiding them towards certain design philosophies inherent to these tools 4.20. In the context of this class assignments hint at parametric design, prompting an implicit bias towards PDEs and more precisely tools like Grasshopper© and, by extension, a stylistic preference sometimes mirroring the works of architects known for their parametric designs. Beyond the class objectives, some students express a desire to justify their use of Parametric Design Environments (PDEs) by aiming for “parametric-like” buildings, however that logic is not mentioned when talking about other tools used in design studio classes. This highlights the impact of the assignment, which implicitly integrates a demand for a specific tool, not just on task execution but also on the content of architectural production.

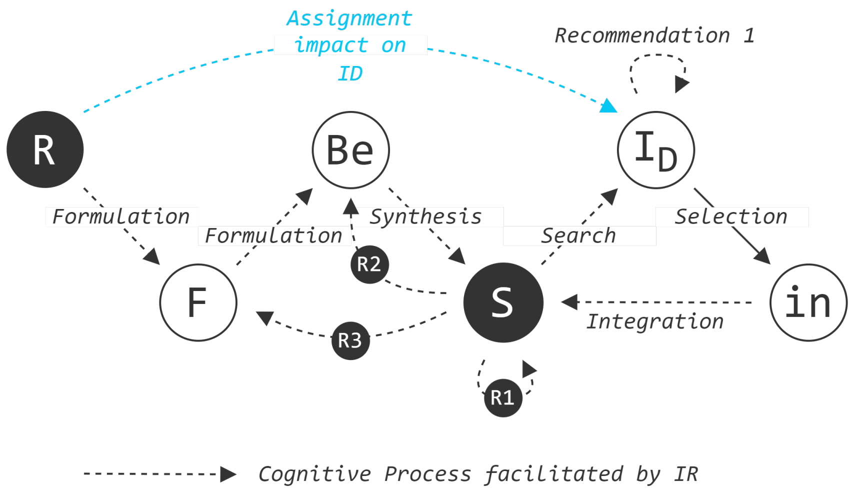


Figure 4.19: *Keywords from the assignment are directly used in IR as well as tool related keywords such as the tool's name.*

> *21S12 : "For the 3rd assignment, that is what we did: we typed in: tower and Grasshopper©".*

This early structuring around tool-centric keywords often serves as a preliminary step in the design process, aiming to facilitate reformulation of design concepts or assist in the initial refinement of keywords (R1). Such a strategy underscores the seamless integration of information retrieval right from the onset, laying a foundation that is both informed by and reliant on tools and assignment descriptions.

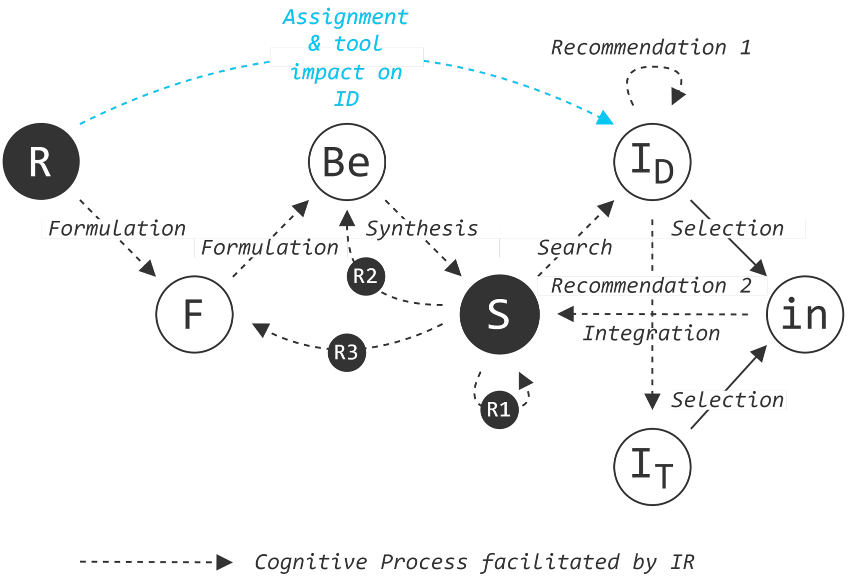


Figure 4.20: *The proximity of search semantics to the tool results in recommendations that are heavily tool-centric. This outcome leads to the integration of tool-related information into the structure.*

4.2.3 Tool as a vector for design

The insights from the interviews shed light on the transformative role of digital tools in their design processes, highlighting a process that often bypass references in favor of tool manipulation and procedural knowledge acquisition (see Figure 4.21). This process is not linear but characterized by a dynamic interplay between seeking design ideas and the technical skills required to implement these ideas. This approach bypasses the conventional stages of idea generation, instead relying on procedural information, obtained in order to expand tool knowledge, as the catalyst for design.

> *22S11 (id11-14): "For the tower, I looked at the UI symbols. I took all the stuff that looked interesting and tried to make it work. I haven't planned anything and tried to make it work on Grasshopper©. I took what I saw and tried things randomly".*

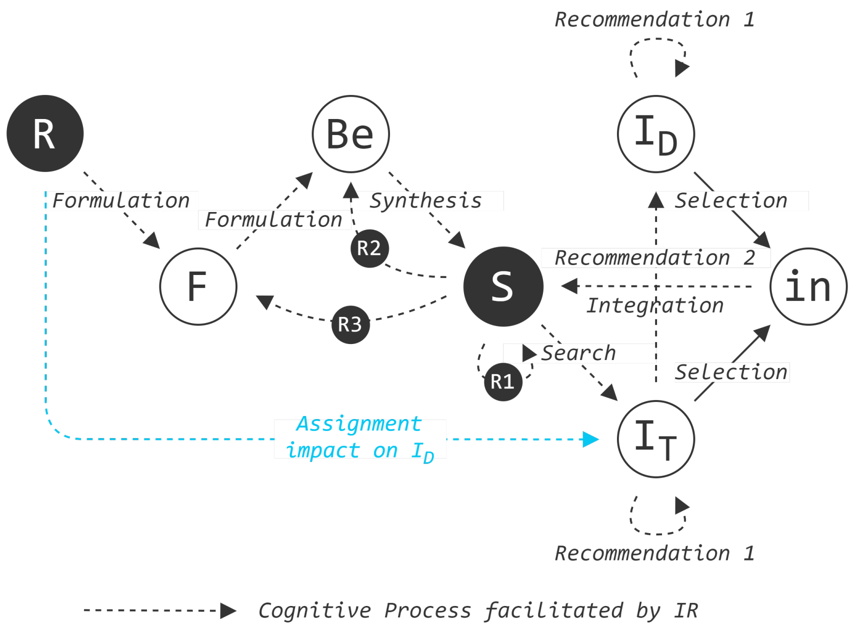


Figure 4.21: *Process facilitated by IR and directed at* I_T *from which* I_D *is derived. The search for* I_D *exists within the tool information affordance space.*

This behavior is supported by a vast ecosystem of video tutorials, which serve dual roles: as avenues for technical skill acquisition and indirectly as sources of inspiration for I_D. These resources enable students to visualize design references as well as the technical procedure to achieve them, effectively bridging the gap between conceptualization and realization. The reliance on such resources highlights a shift towards procedural knowledge as a critical component of the design process, where the technical capabilities offered by tools like Grasshopper© become intertwined with design exploration. Once the structure is set, PDEs allow for facilitated R1 which are even regarded as offering "total freedom" providing the opportunity for exploration through a set of parameters.

> *22S09: "Here for the tower, I'm not sure you remember, but in my tower I used polygons. There we determine the number of sides we want, the soft angles etc... From there we have a large panel of possibilities that*

opens up et it gives total freedom".

The focus on the tool, given its complexity, is not unexpected. Students indicated that mastering the tools demanded most of their cognitive investment. Notably, during the interviews, none of the students mentioned difficulties related to the design aspect of their tasks, prompting a reevaluation of the survey findings regarding perceived difficulty. Moreover, this concentrated effort on the tool category of information has led to specific preferences concerning information type and sources. When searching for I^T, there is a strong preference for procedural information that is video based.

4.2.4 Design strategies driven by Information source

Images serve as a source of inspiration, encapsulating both conceptual information (I^C) related specifically to architectural aspiration and referred to as “references” and occasionally procedural information (I^P) when images are displaying specific information like a schematic or, as observed in our study, tool specific formatted algorithms. A reference that would have required visual reasoning in more traditional means now delivers visual step by step information.

The dual function of images as sources of inspiration and instructional guides underscores their significance in the design process. The visual nature of architecture as a discipline naturally gravitates towards imagery as a medium that conveys complex ideas succinctly, bridging the gap between abstract concepts and tangible design solutions. However, students reported filtering images based on estimated feasibility or perceived affordance rather than contextual value. It might be argued that the filtering of those reference images was based on the visual reasoning capabilities and computational tool related knowledge of each student. Additionally, images are recognized for their role in facilitating communication, often becoming focal points of discussion and decision-making in collaborative settings. However, images are not the only source of conceptual information (I^C); videos often supplant them, offering dynamic and perhaps more engaging ways to convey information and ideas.

When asked to describe their design process, all participants mentioned “YouTube” as either the stage following the first concept ideas or as a key source for idea generation. Videos, and in this case tutorials specifically, extend the tool knowledge by offering step-by-step guidance via tutorials. This format not only supports the acquisition of procedural knowledge but also fosters an environment conducive to self-regulated learning therefore reduced cognitive effort for integration. The tutorial format responds to the learning demand for information that is not only accessible but also actionable, facilitating the transition from information to application rather than create within the design process. This is in line with instructional effects depicted in cognitive load theory specifically the worked example effect. However, the lack of instructional supervision means that these examples might unintentionally become the design itself, indicating that while the ease of cognitive load makes this format appealing, it could also have a substantial impact on cognitive load driven design decisions.

While videos are commonly identified with tool-related information (I_T), some students have also pointed out their role as "references," hence acting as sources of both I_T^P and conceptual knowledge (I_D^C) (see Figure 4.22). These videos offer a visual representation of the target, PDE supported, structure, coupled with the added value of a visual script or "recipe" for synthesis. This dual function significantly reduces the cognitive burden associated with selecting information that would have otherwise perceived as cognitively heavy such as curiosity driven or analogically distant stimuli. This insight may also shed light on why fewer students report using images as their primary references, showing a preference for video-based content instead during the interviews or the relatively low usage of images reported in the survey. Moreover, recommender systems that connect images to videos (e.g., an image serving as a thumbnail for a video) might blur the lines between design related knowledge expansion ($K_D \rightarrow$) and tool related knowledge expansion ($K_T \rightarrow$), leading to potential misclassification of learning strategies. This ambiguity in categorization mirrors a similar uncertainty in the students' design process, where I_T becomes closely tied to reference material I_D. Interviews reveal that as students grapple with mastering new tools, there's a tendency to prioritize tool-related procedural information over conceptual design knowledge, especially in the context of complex create tasks.

Beyond the example of the thumbnail, architectural content often appears intrinsically linked to parametric tools. One student mentioned working on developing a reference they initially discovered as an image and eventually found a tutorial to create it. This further indicates that despite the geometric complexity of parametric designs, they are often more accessible (requiring less cognitive effort) due to the nature of the PDEs. This observation supports the notion of a tool-influenced style that reinforces itself. For example, the student's reference to the Fairtrade Milan project by Fuksas, for which they located a suitable tutorial, exemplifies how parametrically inspired designs frequently come with ready-made guides due to their strong association with specific tools. Despite the inherent geometric complexity of such projects, the ease of reproduction increases the likelihood of finding similar projects and consequently makes it easier to find corresponding I_T.

Surprisingly, students also indicated that they turn to video tutorials in search of factual information, a method that might seem time-intensive at first glance. When queried about their preference for this approach, they explained that

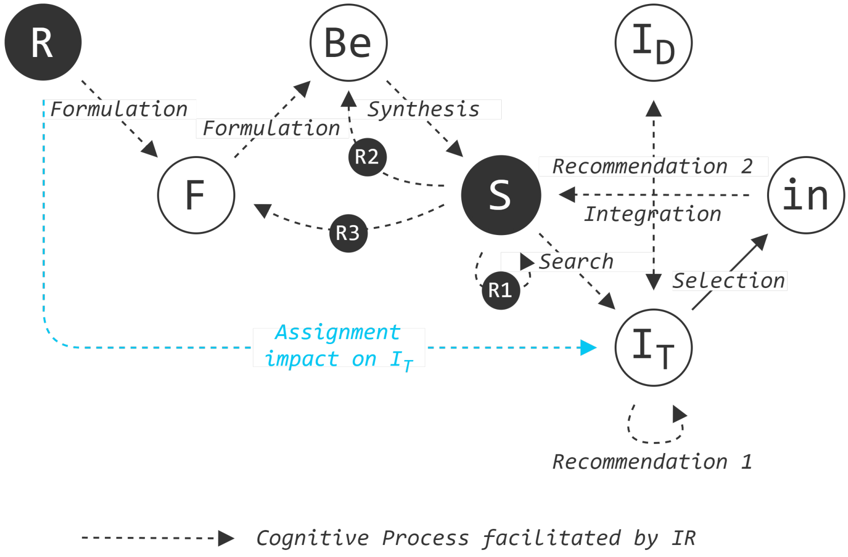


Figure 4.22: *Process facilitated by IR and directed at* I_T *from which* I_D *is passively derived.* I_D *appears therefore as unconscious discontinuity within the design process.*

generating precise search terms proved challenging, whereas navigating through broader contexts was simpler. Additionally, they found that recommender systems played a crucial role in refining their search queries. Video platforms like YouTube© offer visual cues and related content, enhancing the search experience. Once again, this suggests the lack of prior conceptual knowledge makes it difficult to render explicit search inputs. Furthermore, the automatic translation of titles from English to French was particularly valued, as language barriers could otherwise hinder information access. Despite the survey results showing a tendency to invest effort into acquiring factual knowledge, interviews suggest that this effort is relatively minor, primarily due to the challenges encountered alleviated by going through procedural information instead.

> *21S02 (id111-112): "For example, some groups would base their design on a tutorial. That is not what we did, it was really about finding an answer to our problem but not retrieve the complete algorithm".*

22S02 (id64-65): "The video is not for the entire algorithm but rather find specific operations".

This pattern reveals an interesting dynamic: just as students seeking design references frequently encounter video tutorials, those in search of specific factual information often stumble upon procedural content. This suggests that, through video tutorials, students may not be specifically targeting factual knowledge; instead, they are engaging with highly contextualized procedural knowledge. This indicates a shift in how information is sought and absorbed, highlighting the significance of context and the utility of video tutorials in facilitating a deeper understanding of both procedural and, indirectly, factual knowledge.

In exploring the effort involved in utilizing videos, several students reported watching numerous videos not directly related to their design task as a means to broaden their tool-related knowledge. Some noted that this exploratory behavior inadvertently sparked new design ideas, illustrating how procedural information search can sometimes lead to unexpected conceptual ideation. This process demonstrates the fluidity between building tool related conceptual knowledge and the emergence of new design concepts, underscoring the interconnectedness of procedural and conceptual knowledge but also tool and design knowledge.

22S16 (id149): "If we can, we look at a lot of videos that will have different outcomes and we will try to extract valuable knowledge for our own algorithm".

Conversely in one instance, one student encountered a video that perfectly matched their initial design concept but opted not to view it due to its length, leading them to alter their design direction. This decision highlights the potential impact of video length and perceived effort on students' willingness to engage with certain information, which can, in turn, influence their design choices. Such scenarios suggest critical balance between seeking inspiration and the practical constraints of time and effort involved in integrating information.

21S05 : "And the video was exactly what we we're trying to achieve but it was way too long".

It might seem logical to assume that with increasing experience, reliance on procedural information (I^P) and specifically videos would diminish across three tasks. However, all members of a specific group explicitly stated they shifted towards an even more I^P-focused approach to better align with the materials they could access more readily. This adaptation was a direct response to the challenges they encountered in the first two exercises, during which they attempted to minimize their dependence on information retrieval. In essence, they developed their strategy based on the principle of least effort, optimizing their process to leverage the most accessible resources effectively.

> *21S13 (id152-155) : "(...) In fact, because there were two of us, we watched a tutorial, just one for the second exercise. And we realized that it really helped quite a bit. We were in a rush, so we couldn't finish it all the way. But that's why we decided, for the third one, we'd start with that."*

Finally, it appears that videos related to design tools serve primarily the documentation process for an existing structure as there was no further reformulation. Due to the absence of detailed information or specific guidance within these videos, the initial design concept may undergo unintentional deviations with no chance of going back. This observation suggests that design evolution is a natural part of engaging with and developing tool proficiency. Essentially, while designers may not initially intend for their projects to shift direction, these adaptations become inevitable as they delve deeper into the tool's capabilities and constraints usually too late in the project to hope any further reformulation. To further understand this dynamic, a correspondence between the sources and types of information within interactive search systems is outlined (see Table 4.1). This analysis helps in identifying how different sources of information contribute to or influence the types of knowledge that designers rely on throughout the design process.

Table 4.1: *Correspondance between information types and sources.*

Interactive Search Systems	I^F	I^P	I^C
Text	-	-	I_D
Images	-	I_T	I_D
Videos	I_T	I_D, I_T	I_D, I_T

Some students have displayed meta-cognitive abilities in approaching their process. One student mentioned the importance of clearly defining the problem by considering the social aspect of the assignment before starting the search process. Another group has voluntarily avoided searching for I^C in I_D as they were aware of the bias it might bring to their design. However they ended up trapped later on as they couldn't find any related I_T to what they had planned originally therefore falling into time constraints and having to rely on an unrelated tutorial. Thus, the necessity to search for I_T remained unavoidable. This situation points to a critical insight: when I_D and I_T are intertwined within the information landscape, the potential for discontinuities escalates. As mentioned above the architecture resulting from using parametric design seems tied to the tool itself. Finding corresponding tool information for parametrically specific references is easy however given other architectural typologies finding I_T is harder and necessitates more effort into the definition of search inputs. Navigating this interconnected space demands a heightened level of effort to seamlessly integrate the design process with the tool's capabilities, underscoring the complexities of maintaining originality while leveraging digital resources. It suggests that the perceived affordance acquired through initial search seem to help in developing designs that are actually more prone to be generated. This also implies that the assumption regarding the available information only serve certain types of design that do not promote generativity.

Course material, also mentioned by participants as a valuable source of information, predominantly consists of video content and is also categorized under procedural information. This material, often derived from previous classes, is accessible online, meant to provide students with the opportunity of looking back at learning resources.

> *22S01 (id83): "I don't even remember looking at a video for the second assignment. It is simply based on the course material when we looked at how to place points on a surface and how to move them".*

The almost absence of printed material from mentioned information sources highlights a preference for digital resources. This trend underscores the necessity for digital literacy, as students are required to go through an extensive online repository of materials, favoring the efficiency and accessibility of web-based searches over conventional library visits. The preference for digital information retrieval, including the use of images and recommendation systems, suggests a less effort-intensive approach than traditional methods, fitting seamlessly into a design process that is becoming increasingly knowledge-intensive with complex evolving tools such as PDEs. The few mentions of books are related to the design process outside this class and are usually following a teacher's advice on a specific reference. However, while digital searches streamline the information retrieval process, the significance of human intermediaries in information retrieval should not be overlooked.

> *22s14 (id117-*119): "During the course you mentioned Arturo Tedeschi. I took the book to see how he worked. That is what allowed me to keep going on our first design iteration".*

4.2.5 People as sources of information and recommendation

While videos emerged as a primary source of information, the role of people, especially monitors, appeared to be important for the majority of students. However, monitor's accessibility was constrained by time and the sequential nature of the design process, introducing a dynamic of anticipation and potential delay in receiving guidance. Monitors are usually not mentioned as part of the process unless asked specifically in accordance with the survey's results. It is important to note that monitors were instructed to only answer specific questions related to the tool, focusing primarily on factual knowledge, in order to minimize their influence on the overall design process.

> *22S16 (id:15): "When we had very specific questions, we asked the student monitors but that didn't happen for the first assignment".*

Formulating queries required effort similarly to formulating keywords, particularly since outside of class, communication with monitors was limited to messaging. This reliance on text-based interactions probably led to underutilization of other resources like forums, blogs, or even teacher consultations. In contrast, monitors became invaluable within the classroom setting, where students could articulate their questions through a blend of words, images, sketches, and direct interactions with their digital models. This rich mode of communication enabled monitors to serve not only as providers of specific factual information but also as sources of procedural knowledge. While students were encouraged to seek precise information from monitors, the inherent ambiguity in their queries (a sketch for instance can be ambiguous) sometimes led to unexpected responses suggesting that might have had an impact on their design however given the lack of granularity, it can hardly be demonstrated. Additionally, some participants utilized monitors for procedural guidance beyond the classroom, benefiting from the opportunity for in-person meetings which circumvented the limitations of chat-based support. Those interactions suggest monitors were thus used as a form of recommender system.

> *21S02 (id:147): "And sometimes, they sent back the Grasshopper© file so they could understand how they did it".*
>
> *21S03 (id209-210): "Eventually they helped us but they proposed things that were too complicated that we couldn't reproduce. Eventually we told ourselves that it was too complex and that we should simplify like for the preceding assignment".*

Less expectedly, the group dynamic has played a significant role in interacting with information. Like monitor the group doesn't appear as part of the design process except for one group. The role of group work provided a platform for shared knowledge and collective decision-making. This collaborative environment fosters a collective working memory, enhancing conceptual knowledge acquisition. The reliance on group dynamics underscores the importance of social interaction in the architectural design process even more so when considering the inspiration process. The value of the group within the design process is often not recognized yet they report sharing sketches they draw to each other for communication which forces formulation and synthesis, in order to agree on a common design path. Perhaps that is also the reason the group dynamic is also reported negatively. While fostering collaboration and shared understanding, the integration of parametric design environments (PDEs) within the group context has, in some instances, led to an uneven distribution of responsibilities, inciting conflicts. PDEs are seen as intricate documentation tools whose task fall on the most knowledgeable members who eventually end up steering the design process as well as the output similarly to a recommender system. However, people interaction has lead to different design dynamics compared to interactive search systems specially in regards to the type of information. While search system and their respective recommender algorithms necessitate very few input such as the name of the tool and a few keywords extracted from the assignment, communication with people seems to require an initial structure (see Table 4.2). Moreover, queries made to people are mostly tool related except of course within the group as they are designing together. Conversely, using interactive information retrieval system design related information I_D and tool related information are often intertwined I_T.

Table 4.2: *Matrix of search strategies correlating sources, types and categories of information. People as sources require an initial structure for search query (D→). Conversely in interactive search systems information whether* I_D *or* I_T *can drive the initial structure through recommender sytems (*$I_{D,T}$*→D).*

Source / Information Type	I^F	I^P	I^C
People			
Teacher	$D \rightarrow I_T$	$D \rightarrow I_T$	$D \rightarrow I_T$
Monitor	$D \rightarrow I_T$	$D \rightarrow I_T$	$D \rightarrow I_T$
Group	$D \rightarrow I_D$, $D \rightarrow I_T$	$D \rightarrow I_D$, $D \rightarrow I_T$	$D \rightarrow I_D$, $D \rightarrow I_T$
Interactive Search Systems			
Blogs	$D \rightarrow I_T$	-	-
Images	-	$I_T \rightarrow D$	$D \rightarrow I_D$, $I_D \rightarrow D$
Videos	$D \rightarrow I_T$, $I_T \rightarrow D$	$D \rightarrow I_D$, $D \rightarrow I_T$, $I_D \rightarrow D$, $I_T \rightarrow D$, $I_D \leftrightarrow I_T$	$D \rightarrow I_D$, $D \rightarrow I_T$, $I_D \rightarrow D$, $I_T \rightarrow D$, $I_D \leftrightarrow I_T$

4.2.6 Social Media and Information Retrieval

Social media sporadically emerged as a source of inspiration yet it was not mentioned in the survey. The interaction reported by students mostly resembles the passive attention strategy as it's often mentioned as part of the discussion but never as part of the design process. Potentially, that passive attention can lead to further knowledge expansion facilitated by the dynamic nature of information and recommendations across platforms. Social media platforms, algorithmically curate content based on the user's preferences. The visual nature of these platforms also aligns with the information preferences regarding visual stimuli. Social media platforms, therefore, not only serve as bridges connecting designers with information but also as catalysts for design. However when asked about the difference in information retrieval strategies between the computational class and a more traditional studio, search seems to be a more active strategy. It shows how students actively search for recommendations within environments tailored for stimuli.

> *22S09 (id: 89-90): "And here on Instagram, it is rather funny. We see the resulting form very quickly (because of the short video format of the platform) (...) That doesn't even last 30 seconds where the guy explains this and this et we see the algorithm forming within a second".*

The interactive nature of social media platforms can also foster a community-driven approach to designing and knowledge sharing. Students engage in discussions, share feedback, and collaborate on projects by providing information within these digital spaces, further enriching the collective knowledge pool. This community aspect underscores the importance of social interaction in the architectural design process, highlighting how collective insights and experiences can enhance individual design practices.

> *22S09 (id: 79) : "On Facebook as well, I found a group that used this".*

4.2.7 Conclusion in terms of Affordance

As stated in chapter 2, affordance provides a comprehensive view of the interplay between design knowledge, tool knowledge and information retrieval in the design process.

Some students demonstrated metacognitive skills in strategizing their design process. For instance, one student highlighted the necessity of defining the problem clearly, taking into account the social dimensions of the project before initiating the search for information. This reflects a thoughtful approach to framing the design challenge, which can significantly influence the direction and efficiency of the search process.

> *21S07 : "They told us to make a bridge therefore we looked at a reference et we started from there. Later we realized that when we were working like that we weren't discovering much. We limited ourselves to the objective and that is it. We didn't have any freedom in our research.(...) We started ignoring references and really focusing on searching parameters...".*

Similarly, another group intentionally avoided searching for conceptual information (I^C) within the domain of information retrieval I_D, mindful of the potential bias it could introduce into their design. This decision, however, led to unforeseen challenges when they were unable to locate a tutorial that matched their original concept, resulting in time constraints and forcing them to resort to an available tutorial. This scenario underscores the complexity of navigating information retrieval with an intention to preserve originality in design.

> *21S07 (id258-265): "Therefore, in this case, dit it end up resembling the initial idea ? Yes, no. Not really I think. No, no. Yes, wait. It is just that we made an additional torsion for mor dynamism".*

The experiences of these students suggest that the initial search and the perceived affordances it reveals can play a crucial role in shaping design outcomes, often steering them towards solutions that are more readily achievable rather than novel or generative. This observation raises questions about the nature of available information and its tendency to support certain types of design approaches over others, potentially limiting generativity. It also speaks to the importance of tool affordance and usability, the accessibility of information, and the role of digital literacy in enabling designers to effectively leverage information retrieval in support of their creative process.

In conclusion, the insights gleaned from the interviews emphasize the intertwined relationship between information type, source, and category, and how they impact the design process in a class of graduate architecture students studying computational design. Information retrieval often serves as a substitute for the initial structure, making the first designer input dependent on the search input definition. The assignment is highly influential because keywords from its description can be directly used in queries, which risks leading all groups to produce similar queries, turning the design process into an explicit problem-solving activity.

The tool plays a significant role in search activities. Given its complexity, most searches are driven by the tool itself. Ultimately, videos emerge as a pivotal source of information, primarily procedural and tool-oriented but also containing factual and design-related details. This reliance on tool-specific procedural videos raises questions about the nature of available tool information and its tendency to support particular design approaches over others, potentially limiting generativity. People as in-person information source seem to alleviate those effects however relying on other people can mean submit to other ideas similarly to a recommender system. Additionally the amount of information retrievable from another person is comparatively very limited.

This relationship underscores the evolving landscape of architectural education and practice, highlighting the need for a curriculum that not only encourages design exploration but also equips students with the skills to navigate and utilize digital resources effectively. The affordance framework used next will provide further nuance for understanding those dynamics, advocating for a more informed, intuitive, and literate approach to architectural design in the digital age.

4.3 Logs

The logs focus on information category. Based on the principles depicted in the background, different behaviors were observed and are connected to information retrieval pertaining either to Design or Tool category. The coding scheme is built following the principle of complementarity of subsystems in affordance. The two subsystems depicted are design knowledge K_D and tool knowledge K_T. Thus information retrieval appears as the expansion of either or both subsystem. If design related information appears as content, it means there has been some expansion ok K_D and the same for K_T. Ultimately the structure appears at the intersection of both K_D and K_T (see Figure 4.23). It is relevant here as the content only exists as structure. A structure can be synthesized through a sketch however it might not exist within the architect's parametric tool knowledge which is the goal structure necessitating information retrieval.

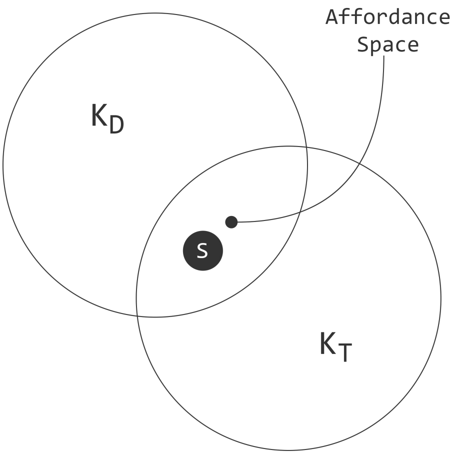


Figure 4.23: *The structure exists within the affordance space at the intersection of the subsystems that are design knowledge* K_D *and tool knowledge* K_T *.*

Thus the coding scheme depicts different scenarios inherent to knowledge expansion through information retrieval. K_D and K_T appear solely whenever there is no information retrieval visible in the presentation. $K_D\rightarrow$ and $\leftarrow K_T$ represent the expansion of respective knowledge through corresponding information category retrieval. The arrows direct to a central figure that is the structure. $\circ K_D$ and $\circ K_T$ represent clear discontinuities within the design process meaning there has been a major reformulation (reformulation 3) of the initial structure. That last scenario can be the result of 2 scenarios: either the initial structure serves information retrieval but eventually some unexpected information comes along prompting a shift in design ($K_D \rightarrow \circ K_D$ and $K_T \circ \leftarrow K_T$), or there isn't any search in that category and the other category brings in the unexpected information ($K_D \circ K_D$ and $K_T \circ K_T$). For instance a sketch might trigger information retrieval towards I_T and through that search the architect finds I_D he eventually decides to integrate. That last scenario appears as recommendation 2 within the conceptual model where on category of information can be tight to the other. However discontinuity within $K_T \circ$ won't be visible here as it would mean a tool shift but students are required to use a specific tool. Finally $\rightarrow K_D$ $K_T \leftarrow$ represents cases when there is no initial structure. Figure 4.24 showcase each code with its corresponding schematic representation.

The unit of analysis is represented by each group for each assignment resulting in 42 codes for both design and tool knowledge expansion (see Table 4.3).

Table 4.3: *Overall results using the coding scheme for both 2021 and 2022 and each group.*

Gr.		K_D	K_T		K_D	K_T		K_D	K_T
21	X1			X2			X3		
A		$K_D \rightarrow$	K_T		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow$	$\leftarrow K_T$
B		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \circ K_D$	$\leftarrow K_T$		$K_D \rightarrow$	K_T
C		$K_D \rightarrow$	$\leftarrow K_T$		K_D	$\leftarrow K_T$		$K_D \circ K_D$	$\leftarrow K_T$
D		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow \circ K_D$	$\leftarrow K_T$
E		$K_D \rightarrow$	K_T		$K_D \rightarrow \circ K_D$	$\leftarrow K_T$		$K_D \circ K_D$	$\leftarrow K_T$
F		$K_D \rightarrow$	K_T		$K_D \circ K_D$	$\leftarrow K_T$		K_D	$\leftarrow K_T$
G		$K_D \rightarrow$	K_T		$K_D \circ K_D$	K_T		$K_D \rightarrow$	K_T
22	X1			X2			X3		
A		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow$	K_T
B		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow \circ K_D$	$\leftarrow K_T$		$K_D \rightarrow \circ K_D$	$\leftarrow K_T$
C		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow \circ K_D$	$\leftarrow K_T$		$K_D \rightarrow$	$\leftarrow K_T$
D		$K_D \rightarrow \circ K_D$	$\leftarrow K_T$		$K_D \circ K_D$	$\leftarrow K_T$		$K_D \circ K_D$	$\leftarrow K_T$
E		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow$	$\leftarrow K_T$
F		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow$	$\leftarrow K_T$
G		$K_D \rightarrow$	$\leftarrow K_T$		$K_D \rightarrow \circ K_D$	$\leftarrow K_T$		$K_D \rightarrow \circ K_D$	$\leftarrow K_T$

The findings highlight a consistent reliance among students on information retrieval in their design process. The implications of this behavior are multifaceted.

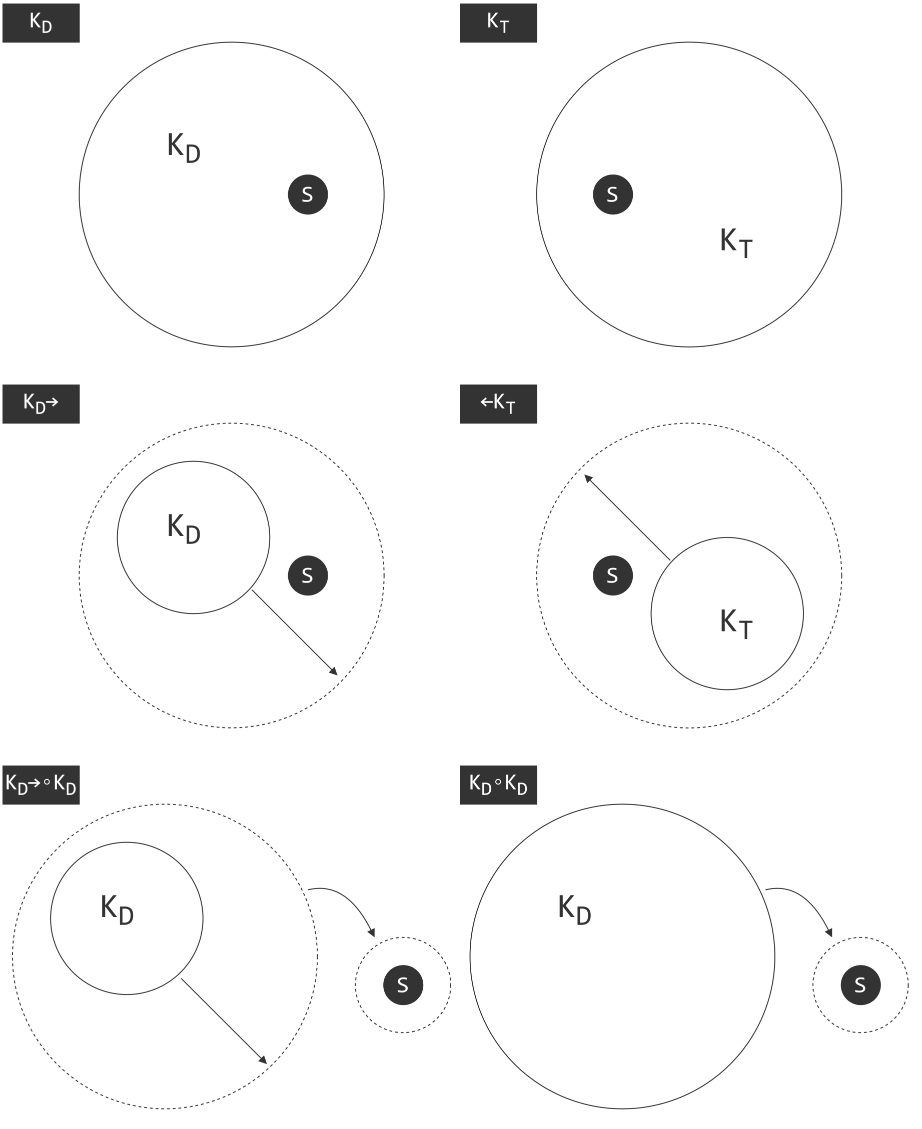


Figure 4.24: *Different content scenarios according to the subsystem model of affordance including both design knowledge* K_D *and tool knowledge* K_T*. The arrows represent the expansion of knowledge and the dashed circle the newly formed knowledge space. Structure* S *always exists within the knowledge space otherwise it would not appear in the content.*

From the analysis, four main retrieval strategies emerge, each underscoring a different aspect of how students navigate the design process: expansion of design knowledge, expansion of tool knowledge, expansion of both design and tool knowledge and finally design shifts.

In the following, to each subsection correspond different groups and assignments characterized by their labels. Each label (YYX#A) refers to the year (YY), the assignment number (X#) and the group letter (A) visible in 4.3

4.3.1 Expansion of design knowledge

21X1A; 21X1E; 21X1F; 21X1G; 21X3B; 21X3G; 22X3A

When students seek to expand their design knowledge, an interesting pattern emerges. It becomes evident that they heavily lean on their prior tool knowledge, even though their familiarity with the tool is limited. This suggests a strong interplay between their existing tool-related skills and their design expansion process. This phenomenon can be interpreted in two distinct ways.

Firstly, the limited proficiency with the tools might impose a constraint on their design abilities, leading to a search for design-related information that fits within the boundaries of their existing tool expertise (Figure 4.25). In this scenario, design expansion is driven by the inherent limitations of their tool capabilities leading to finding inspiration that accommodates their tool expertise. The research design suggests information is the cause of negative impact yet in this case it suggests the opposite. The lack of information retrieval becomes detrimental to design.

In 21X1G, being beginners with the tool, it might be argued that inspiration is validated by the limited tool skills acquired which would explain the lack of variety during exploration (see Figures 4.26 and 4.30). Furthermore the results do not seem analogically distant from the retrieved information suggesting material was specifically chosen as a design goal. However in 22X3A even though the design starts with an initial inspiration the design seemingly evolves beyond simple replication (see Figures 4.27 and 4.31). The latter can be explained because by the time they get to their third assignment the students get more experienced whereas at the beginning it is hard to perceive affordances considering the new tool.

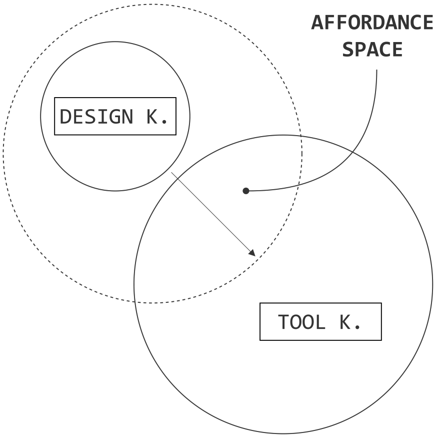


Figure 4.25: *To mediate the lack of* K_D*, the user expands knowledge through information retrieval. This representation assumes that there is a need to expand* K_D *to meet affordance suggesting a tool bias*

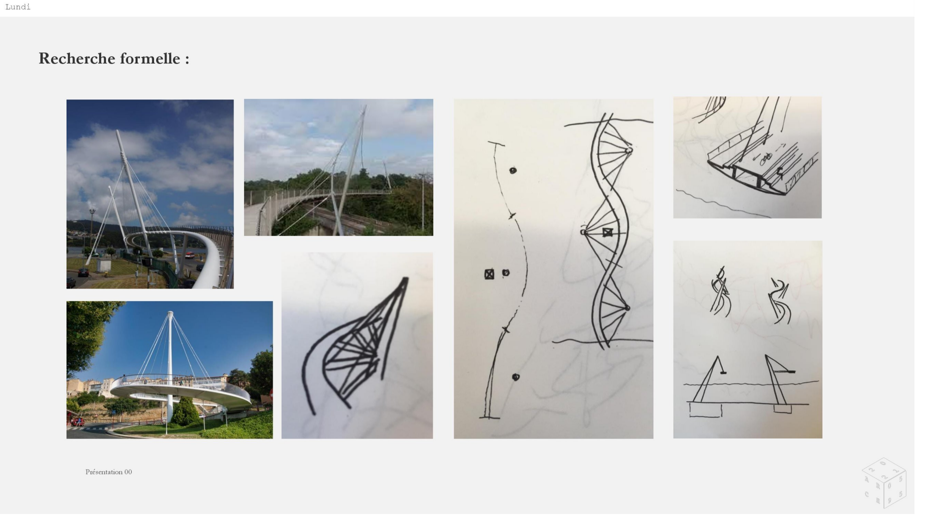


Figure 4.26: *The only used reference appears on the top left from there a corresponding structure is immediately created (21X1G).*

Figure 4.27: *The only reference used by the group (*22X3A*).*

Secondly, it's plausible that the affordance space offered by the tools does exist, yet the students actively choose to further enhance their design knowledge through information retrieval (Figure 4.28). This could indicate a desire for a richer pool of design possibilities that transcends prior knowledge boundaries. Another variant occurs when design knowledge expansion is used to find references to illustrate their development to help design decision making. For instance, in the group labeled 21X3G, the main design decisions were already established, such as stacking three different designs. Here, information retrieval was focused on refining those designs (see Figures 4.29 and 4.32). The group opted for a documentation-focused process, which allowed only limited exploration. However, their work was not biased by tool-related information, or at least the presentation did not show it.

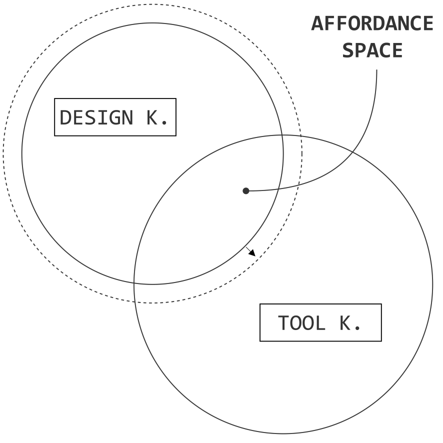


Figure 4.28: *To mediate the lack of design knowledge, the user expands knowledge through information retrieval. This representation assumes that there is no initial need to expand* K_D *to meet affordance*

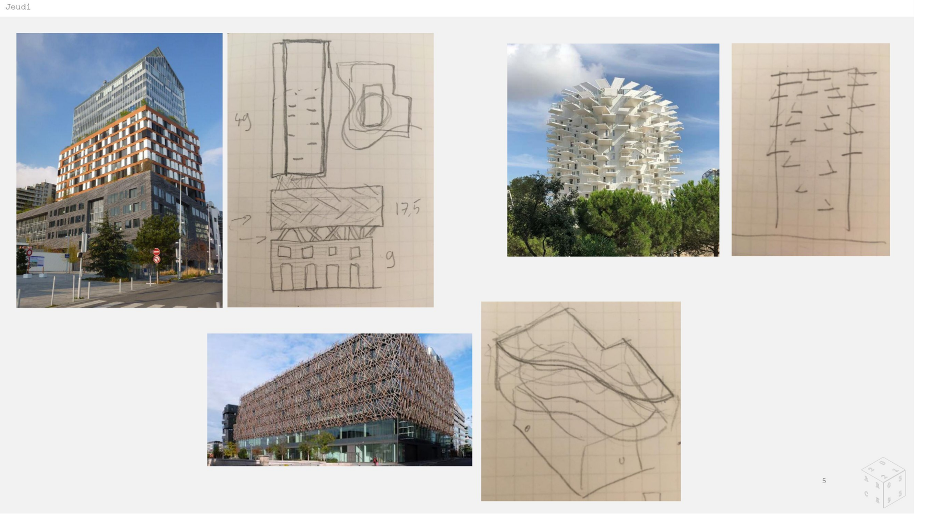


Figure 4.29: *The initial schematic is very clear regarding the intentions and images bring refinements over the general direction (*21X31G*).*

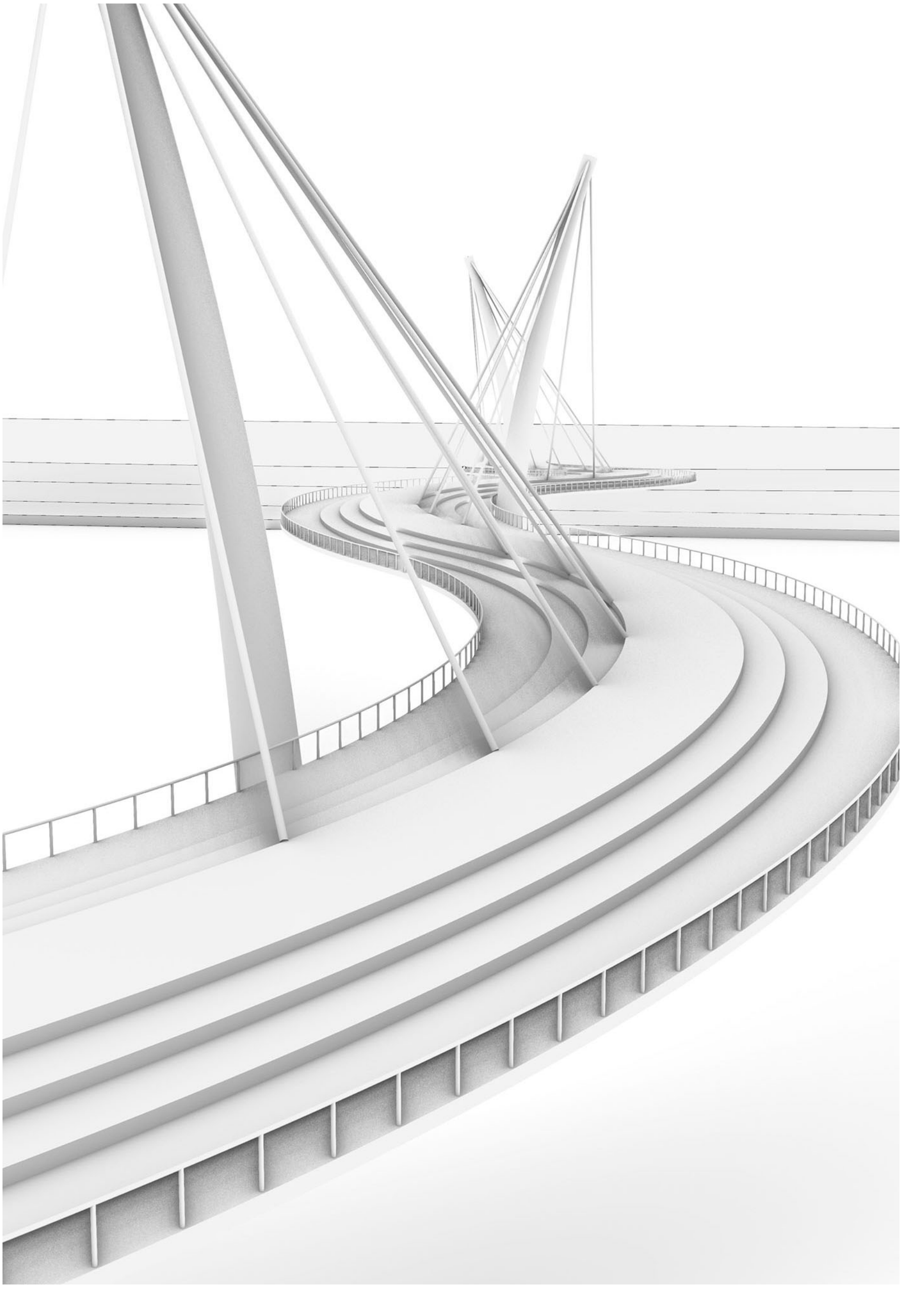


Figure 4.30: Final result for 21X1G

Figure 4.31: *Final result for 22X3A*

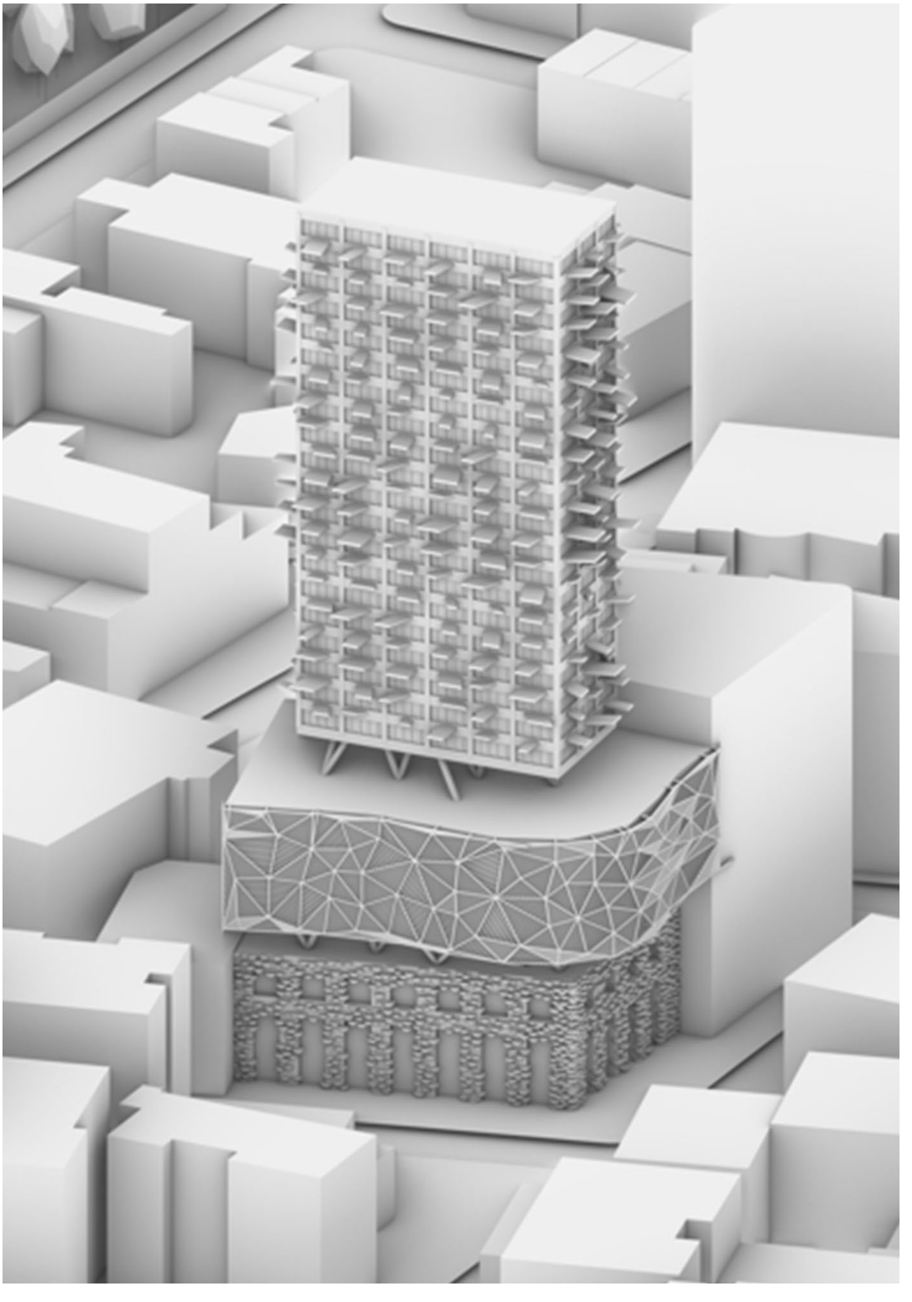


Figure 4.32: *Final result for 21X3G.*

4.3.2 Expansion of tool knowledge

21X2C; 22X3G

There are instances where the students exclusively seek to expand their tool knowledge (K_T), a rather infrequent occurrence. Like the case of design knowledge expansion, two distinct behaviors are plausible, but the data doesn't offer a definitive answer.

On one hand, it's plausible that the affordance space is insufficiently developed, meaning that the range of design possibilities is limited by the inability to create structures using the available tool. This situation requires the students to expand K_T in order to unlock access to broader prior design knowledge (Figure 4.33). 21X2C stipulate during their presentation that they didn't want to get influenced by images and only relied on K_T expansion to solve specific encountered issues (see Figure 4.34 and 4.37). This raises questions about the limitations of prior design knowledge. While information retrieval can undoubtedly influence the design process, it also confines the design space to one's existing knowledge, which can be particularly restrictive for less-experienced students.

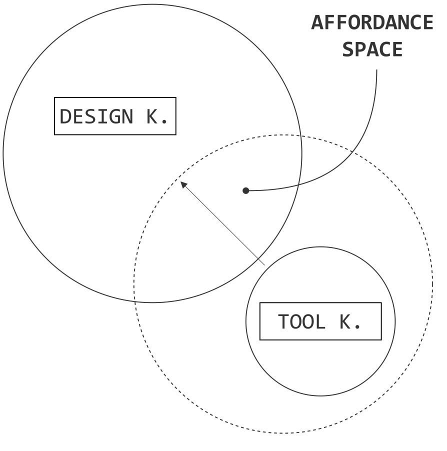


Figure 4.33: *Information retrieval to mediate the lack of* K_T. *This representation assumes there is an initial need to expand knowledge for affordance*

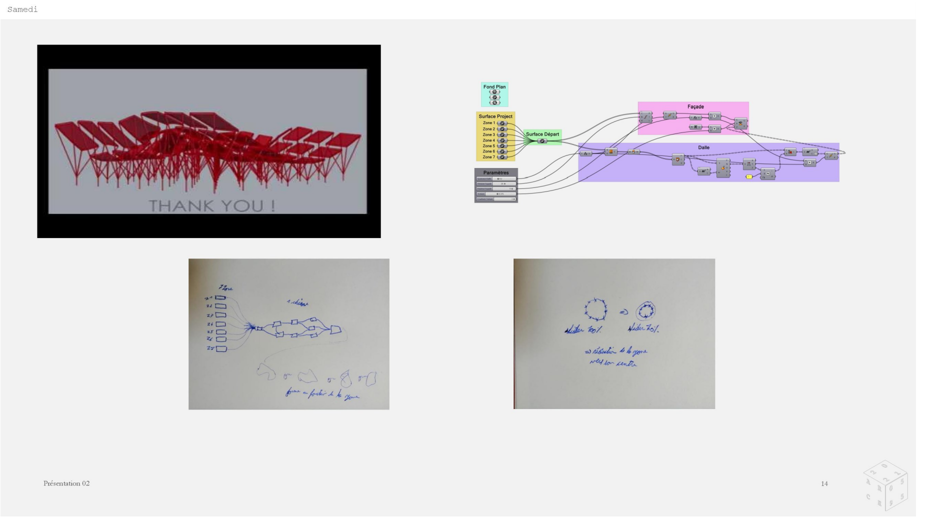


Figure 4.34: *The only information retrieval visible on the top left is a video tutorial (*21X2C*).*

Furthermore, students seem to want to expand K_T to either explore a richer space or simply to fill in knowledge gaps in regards to the tool (Figure 4.35). Alternatively, the existing affordance space could be perceived as constraining, either due to cognitive barriers or limited exploration capabilities. This latter scenario might prompt students to seek ways to transcend these confines through broader expansion of K_T. 22X3G shows a simple development where K_T retrieval serves the refinement of their design, in this case determine the placement of openings through simulation (see Figure 4.36 and 4.38). The group presents a basic form (a box monolith), which suggests that their strategy could limit design when tool knowledge, or the lack thereof, reduces the design space to simple shapes. Thus, expanding design knowledge becomes inevitable.

In both scenarios, the intricate interplay K_D design and K_T, and the choices made regarding information retrieval, highlight the complex decision-making processes architecture students navigate. The factors driving these choices could be a blend of personal preferences, educational contexts, perceived constraints, and the desire for innovation or originality pertaining to the idea of cultural bias and/or convention advanced by Norman. These results emphasize the importance of recognizing not only the presence of information affordances but also understanding the motivations guiding their utilization.

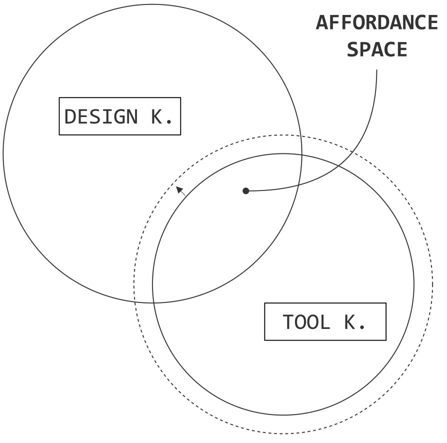


Figure 4.35: *To mediate the lack of* K_T*, the user expands through information retrieval. This representation assumes there is no initial need to expand knowledge to meet affordance*

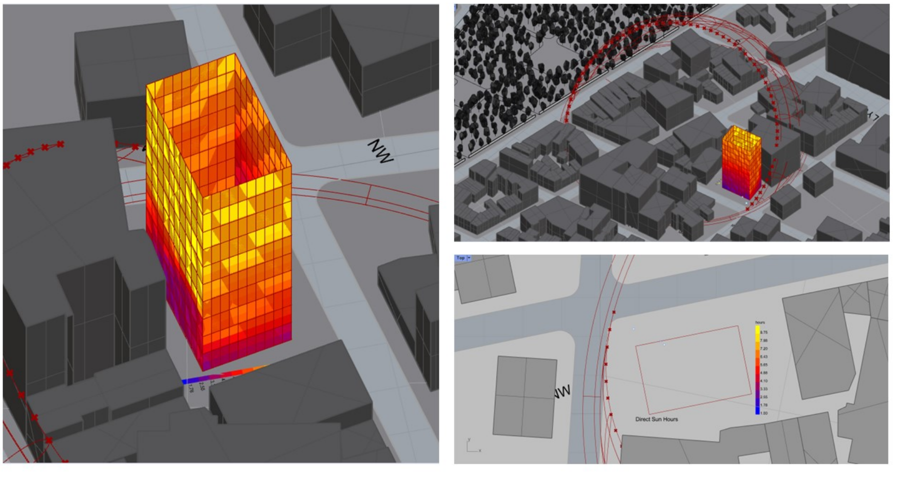


Figure 4.36: *Following a tutorial on sun exposure calculation to then apply it to a predefined form (*22x31G*).*

Figure 4.37: *Final result for 21X2C.*

Figure 4.38: Final result for 21X3G.

4.3.3 Expansion of design and tool knowledge

21X1B; 21X1C; 21X1D; 21X2A; 21X2D; 21X3A; 21X3F; 22X1A; 22X1B; 22X1C; 22X1E; 22X1F; 22X2A; 22X2E; 22X2F; 22X3C; 22X3E; 22X3F

In most instances, the students exhibit a preference for expanding both their design and tool knowledge. This behavior points towards a recognition of the inherent synergy between these domains and hints at a holistic approach to design processes. A deeper analysis uncovers two distinctive scenarios within this behavior.

The first scenario arises when there is a lack of an initial affordance space (Figure 4.39). The expansion on both fronts, design and tool knowledge, potentially creates a context where design-related information is closely intertwined with the tool knowledge needed for execution. An illustrative example might be discovering an inspiring design image, accompanied by finding a tutorial on how to model that specific design using a particular tool (in this case, Grasshopper©). In 22X1C, the images chosen as inspiration turned out to have an associated tutorial that the student initially didn't know about while searching specifically for images (see Figures 4.40 and 4.44). This finding aligns with previous data indicating a strong connection between architectural typologies and the tools used, especially in parametric design where a particular tool becomes almost synonymous with the typology itself. This is often implied through the use of the keyword "parametric" during search definitions, which correlates strongly with the chosen tool. This scenario underscores the symbiotic relationship between design and tool knowledge and demonstrates how information retrieval can bridge the gap between conceptualization and implementation.

The results reveal a consistency in the content of student inquiries across various groups, highlighting a lack of semantic diversity in their queries. This lack of semantic diversity is likely influenced by students' limited prior knowledge, which consequently shapes the simplicity of their queries. In 22X1B for instance, the title of 2 tutorials displayed have the words "pavilion" and "Grasshopper©," which are keywords from the assignment suggesting a poor investment into the definition of search inputs (see Figure 4.41 and 4.45). The interplay between architecture typology and the corresponding tool knowledge further reinforces this trend and can lead to design shifts to better serve available information. This interrelation could lead to the emergence of similar results across multiple groups, even when tasked with slightly different assignments but using similar keywords. However, the specific contextual differences might not always be apparent in these assignments.

The second scenario surfaces during the evolution of an existing affordance space (Figure 4.42). Here, information retrieval takes place within the context of refining an already established design-tool synergy. The expansion in this

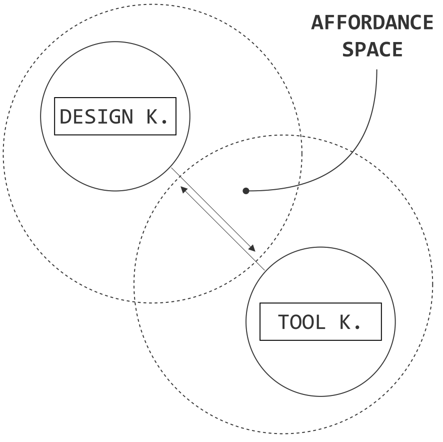


Figure 4.39: *To mediate the lack of knowledge, the user expands both knowledge spaces through information retrieval. This representation assumes there is an initial need to expand knowledge to meet affordance*

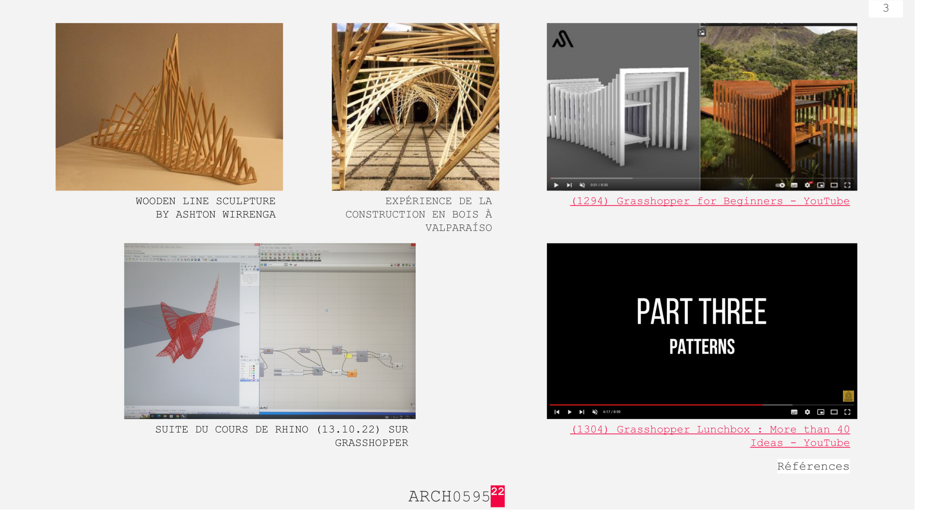


Figure 4.40: *The image reference on the top left is a reflection a a prevuious sketch and a tutorial that seems to correspond on the top right.*

scenario serves as a mechanism for enhancing the sophistication of the original design, indicating a pursuit of finer design details. This behavior mirrors the iterative nature of architectural design processes, where continuous refinement and improvement are paramount.

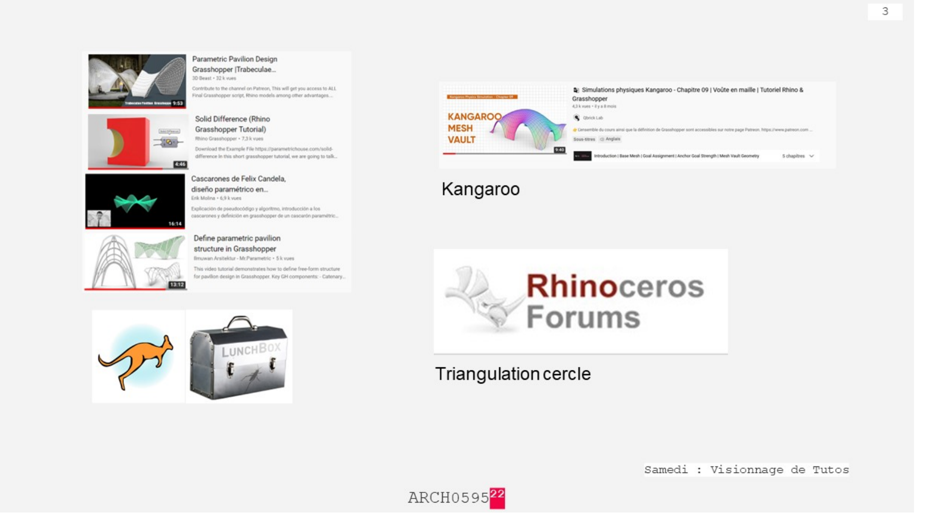


Figure 4.41: *Tutorials display the keywords from the assignment description implying no particular effort into formulation.*

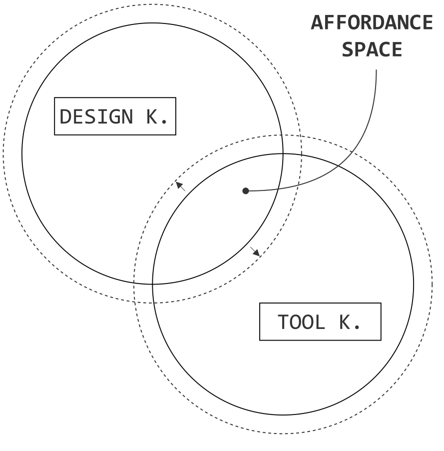


Figure 4.42: *To mediate the lack of knowledge, the user expands both knowledge spaces through information retrieval. This representation assumes there is no initial need to expand knowledge to meet affordance as there is already a space existing at the intersection of design knowledge and tool knowledge*

In some occurrences, students showcase a unique pattern of behavior, where they choose to focus on tool knowledge expansion before making design adjustments. Remarkably, this process appears to transpire independently of the previously mentioned scenarios involving information retrieval or analogies. The underlying motivations for this behavior remain somewhat enigmatic due to its infrequency. However, it might indicate a distinct thought process that emphasizes mastering the tool before fully engaging in design exploration. This approach could stem from a desire for technical competence as a foundation for more informed design decisions. This behavior seem to foster more distant analogy as there are obvious differences between newly acquired K_T and the end result (Figure 4.43 and 4.46). 22X2F for example starts looking at tutorials to end up with totally different results. This eventually suggests how chronology of retrieval can potentially impact the design process.

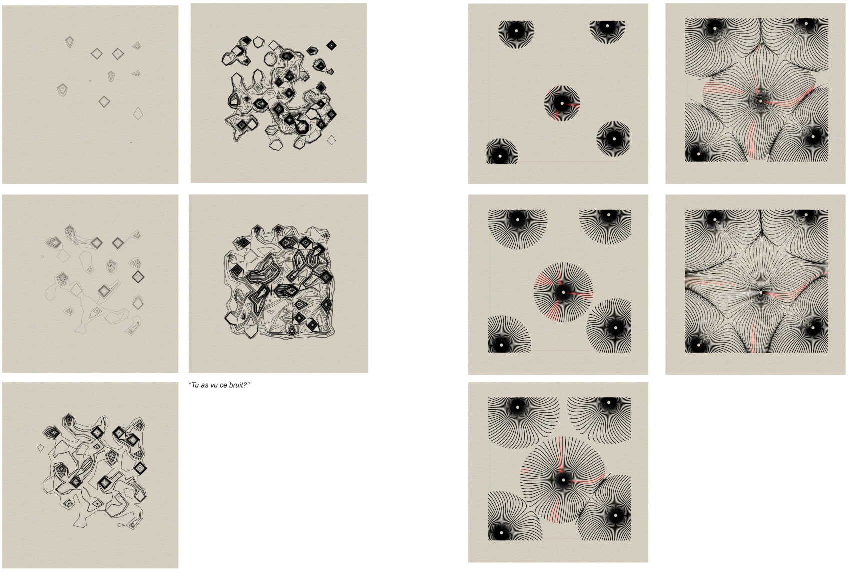


Figure 4.43: *Results following a video tutorial on "fields" in Grasshopper©.*

Figure 4.44: *Final result for 22X1C.*

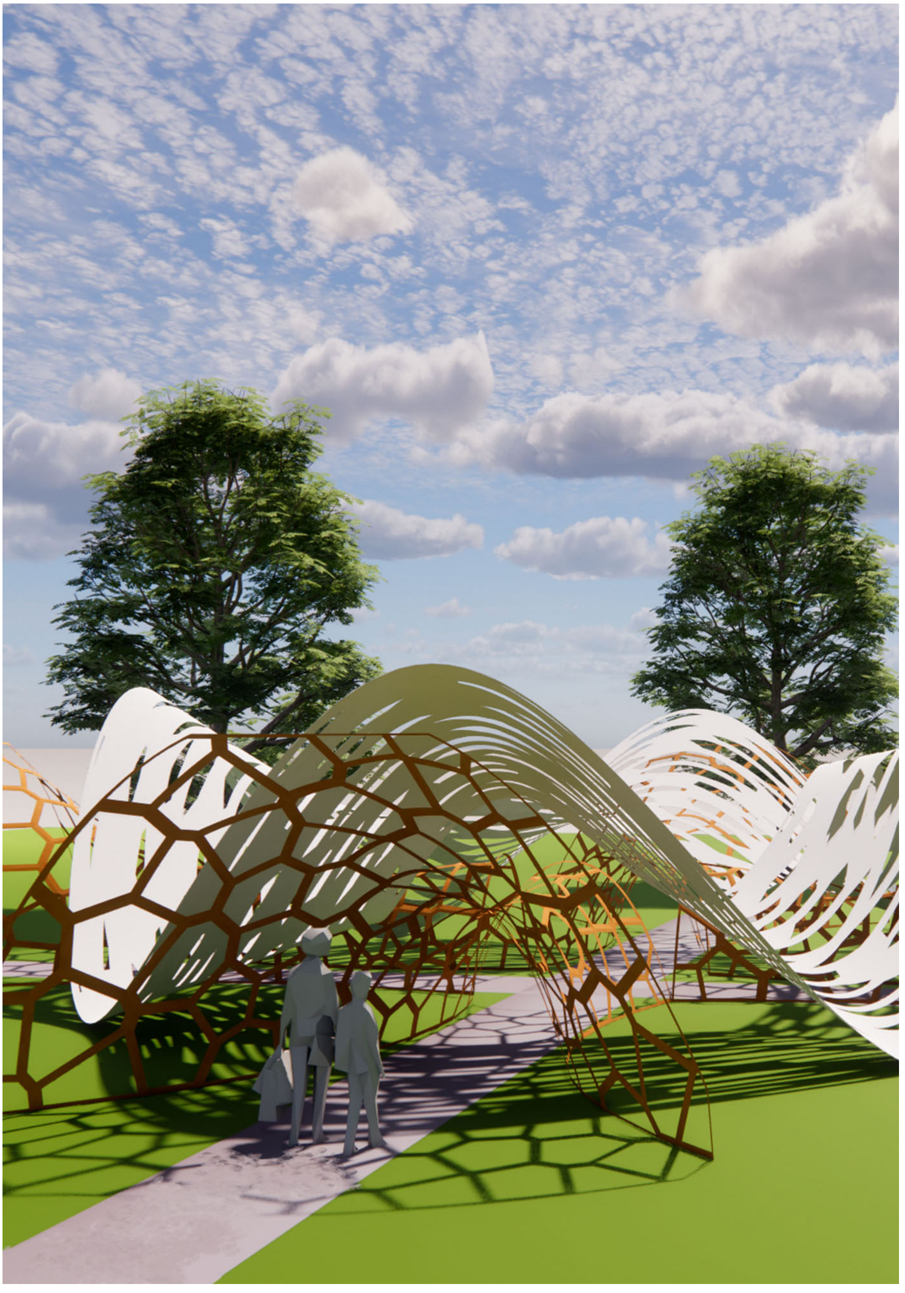


Figure 4.45: *Final result for 22X1B.*

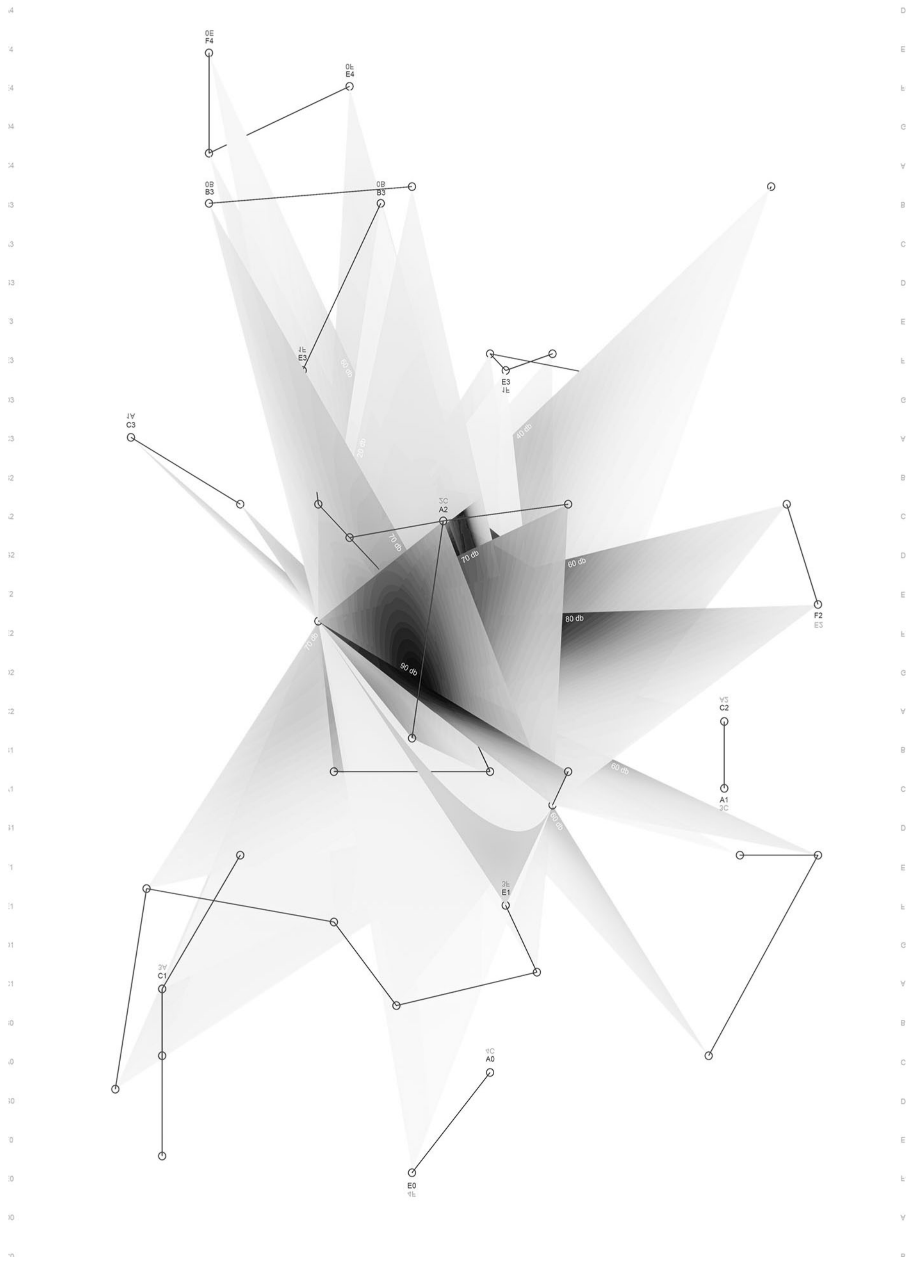


Figure 4.46: *Final result for 22X2F.*

4.3.4 Design shift

21X2B; 21X2E; 21X2F; 21X2G; 21X3C; 21X3D; 21X3E; 22X1D; 22X1G; 22X2B; 22X2C; 22X2D; 22X2G; 22X3B; 22X3D

Most presentations reveal a distinct preference among architecture students to shift their design decisions by relying exclusively on tool-related information (I_T), rather than seeking guidance on the execution of their initial design structure. This observed trend raises questions about the underlying motivations driving such a shift in decision-making processes.

The data collected from the participants highlights a significant emphasis on tool affordances as a primary factor shaping their design decisions. In 22X1D for example, despite various design inspiration and tool knowledge retrieval, the decisions are entirely based on one video tutorial (see Figure 4.48 and 4.50). Furthermore, architecture students appear to be drawn to the tangible and practical aspects of tool information. Within video tutorials for examples alternative design are proposed as worked examples making it easy to end up using that specific design information. This reliance on tool-related information might be a reflection of the students' perceived limitations in translating their initial design ideas into tangible outcomes using complex tools. It is plausible that they prioritize the knowledge of how to effectively utilize the parametric tool in order to bridge the gap between for instance their sketch supported initial structure and realization as a parametrical supported structure. However, this leads to the question of whether their design process is being unintentionally constrained, potentially leading to design fixation issues. The amount of overlap in Figure 4.47 could then coincide with analogical distance from that worked example. However, the level of overlap is difficult to appreciate given the granularity of the data.

Furthermore, an alternative explanation arises from the possibility that these students possess the ability to seamlessly integrate their design ideas with the available tools, yet consciously choose to prioritize tool-related information over existing design affordances (see Figure 4.49). This scenario prompts a deeper inquiry into the motivations driving this decision-making process. Potential reasons could encompass factors such as a desire for conformity with established norms or prevailing architectural trends, a pursuit of design outcomes that align with perceived expectations around the parametric environment, or even a self-imposed pressure to produce results efficiently within the constraints of time and resources. Other explanations might relate to cognitive load. Even if the affordance space exists, the cognitive load associated with it induces a shift towards lesser effort. Students might perceive a structure as achievable but through trial and error that might take time and effort thus they would rather just follow guided instructions even if they aren't in line with their initial

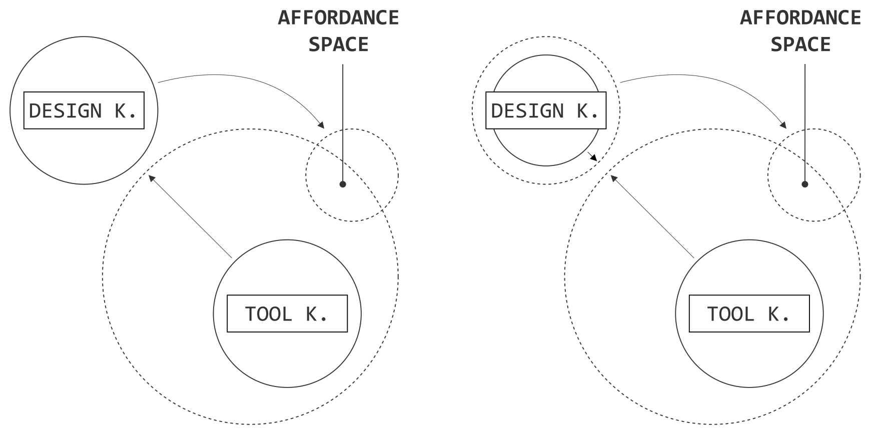


Figure 4.47: *Design decisions are dictated by tool knowledge. The overlap can be related to analogical reasoning. A 100% overlap for example would mean there is no analogical distance therefore no generativity. The right representation shows design knowledge expansion that seems not to serve the design task.*

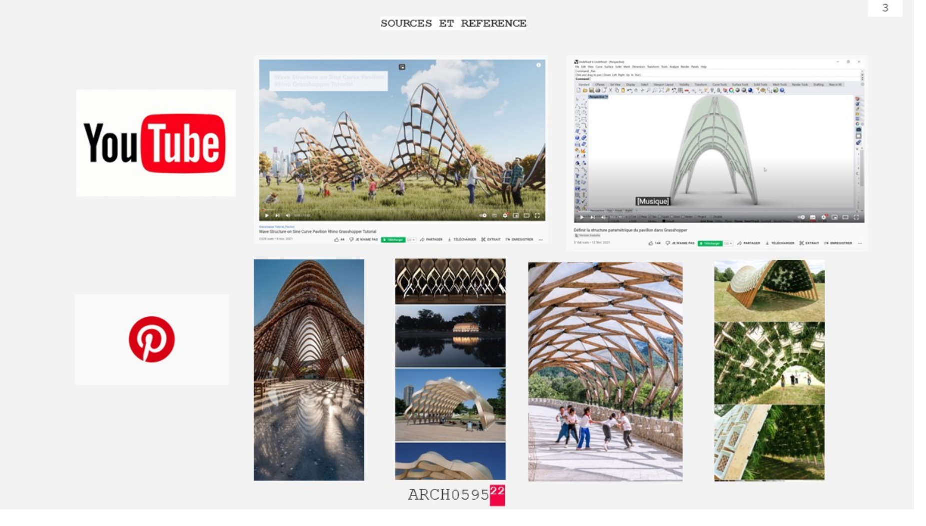


Figure 4.48: *Out of all information displayed, the end result is simply the result of the video tutorial on the top right.*

structure or idea.

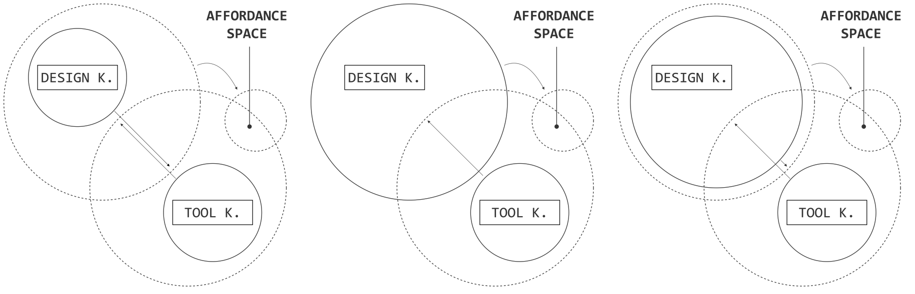


Figure 4.49: *Despite the existing affordance space after information retrieval, there is a shift regarding design decisions towards tool-related information. The three strategies display different efforts in both knowledge expansion strategies.*

In the end, given the lack of granularity, the interpretation must be nuanced. All possible expected design behaviors can be seen in appendix B.

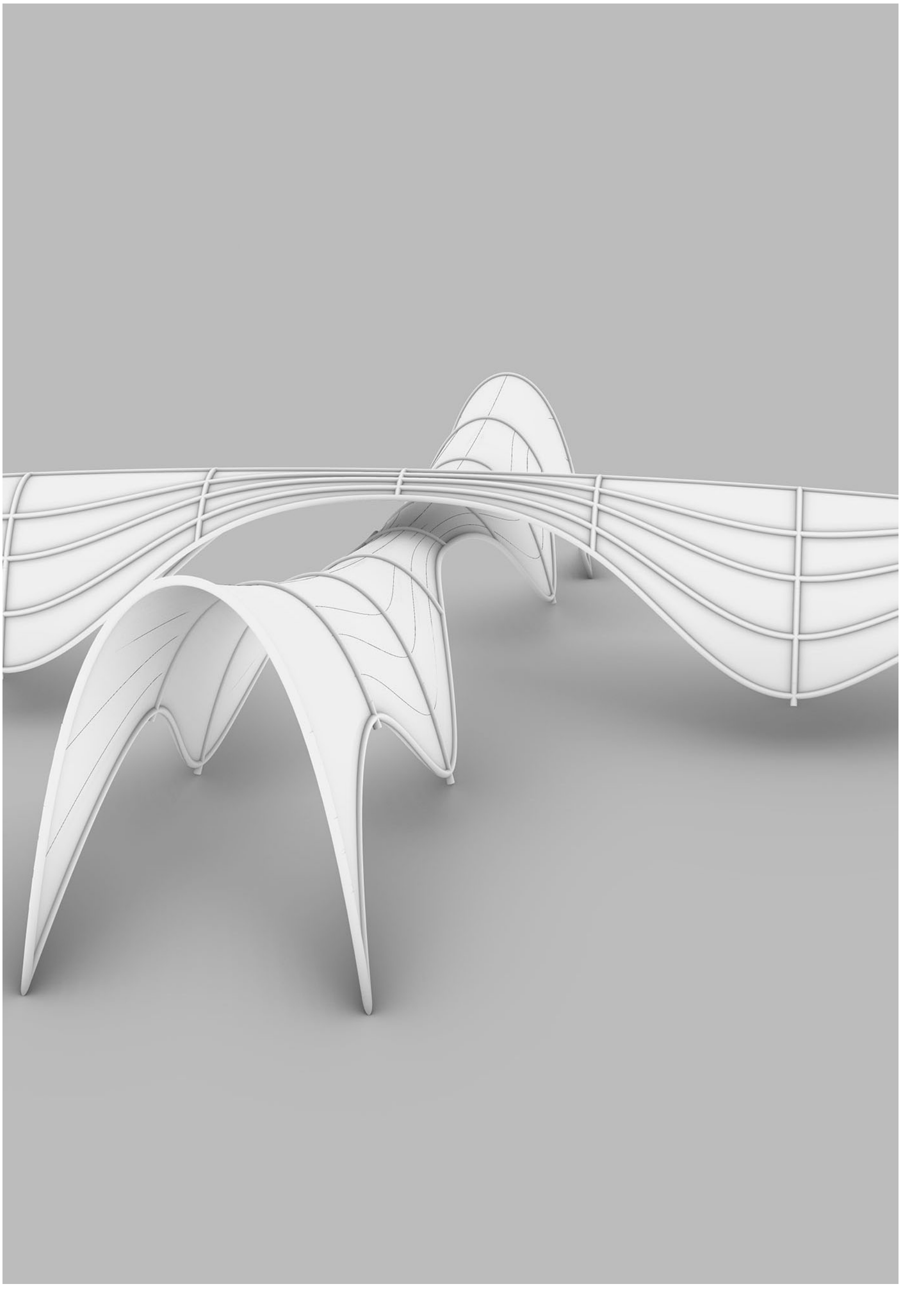


Figure 4.50: *Final result for 22X1D.*

4.3.5 Second cycle pattern coding: learning objectives

Codes derived from the previous hypothesis coding have been grouped into broader categories centered on design description to mitigate the nuanced interpretations that may arise from the preliminary results (refer to 4.4). These categories were then organized into a two-dimensional matrix to better illustrate the impact of information affordances on design and tool knowledge, as well as their interplay. This matrix offers a comprehensive view of these interactions and provides a quantitative perspective by measuring occurrences (see Figure 4.51). Ultimately, this approach helps the class better calibrate assignments to encourage specific behaviors, aligning them more closely with the desired learning objectives.

Table 4.4: *Second Coding is a simplified version that only takes into account design shifts →D and T←.*

Initial Code	Second Code
K_D	D
K_T	T
K_D→	D→
←K_T	←T
K_D→∘K_D and K_D∘K_D	→D
K_T∘←K_T and K_T∘K_T	T←

4.3.5.1 Results in regard to each design assignment

The analysis of data showcased in Figure 4.51 reveals that, across both 2021 and 2022, there was a notable trend among students towards employing a wider range of strategies as the course progressed towards its conclusion.

For the bridge (21X1), two strategies appear almost equally (43% and 57% respectively). Surprisingly almost half of the students report not using information retrieval to expand on K_T. This suggests a significant reliance on user interface (UI) cues or signifiers for guidance. This reliance is particularly notable given that this assignment was their first, implying limited prior experience with the tools in question. The design space is thus very limited given students' poor expertise. Another explanation is that the lack of semantic knowledge may be preventing students from looking for information. Lastly it is possible that students may be making an active decision to conceal the fact they relied on

21X1	D	D→	→D	
T	0%	57%	0%	57%
←T	0%	43%	0%	43%
T←	0%	0%	0%	0%
	0%	100%	0%	

21X2	D	D→	→D	
T	0%	0%	0%	0%
←T	14%	29%	57%	100%
T←	0%	0%	0%	0%
	14%	29%	57%	

21X3	D	D→	→D	
T	0%	29%	0%	29%
←T	0%	29%	43%	71%
T←	0%	0%	0%	0%
	0%	57%	43%	

22X1	D	D→	→D	
T	0%	0%	0%	0%
←T	0%	71%	29%	100%
T←	0%	0%	0%	0%
	0%	71%	29%	

22X2	D	D→	→D	
T	0%	0%	0%	0%
←T	0%	43%	57%	100%
T←	0%	0%	0%	0%
	0%	43%	57%	

22X3	D	D→	→D	
T	0%	14%	0%	14%
←T	14%	43%	29%	86%
T←	0%	0%	0%	0%
	14%	57%	29%	

Figure 4.51: *Distribution of search strategies on a 2-dimensional matrix. Dimension 1 relates to design knowledge and dimension 2 relates to tool knowledge with or without expansion.*

tool related information, perhaps in order to show the teachers that they put in a greater effort.

For the pavilion (22X1), two strategies appear. The visible design shift (→D←T) suggests design affordance is dictated by tool related information retrieval. It is clear for 29% of instances, however this is probably a low estimate as it might not always be visible in the presentation.

For the theater and the series of pavilions (21X2) 14% are actively trying to comply to their original idea, 29% are retrieving information in both domains while the rest has either abandoned their initial idea or didn't even bother ideating, solely relying on tool related information retrieval.

For the exploratory art piece (22X2), it's interesting to see that the overall strategy is shifting more towards tool related information retrieval. It is even more surprising given the lack of constraints. This observation aligns with empirical data in information retrieval theory highlighting the challenges of defining clear objectives in such contexts. The relying on tool related information retrieval is particularly obvious here as well as the deterministic nature of the search engine as most groups ended up following the same video tutorial even though the lack of constraint was meant to free up the students from potential keyword biases (Figures 4.52, 4.53, 4.54 and 4.55)

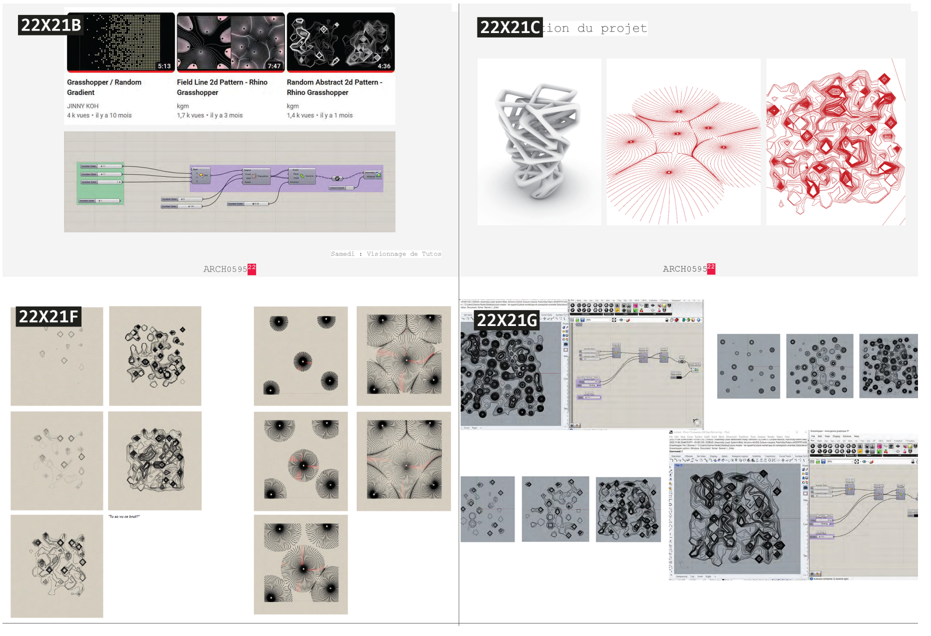


Figure 4.52: *Four out of seven groups relied on the same information despite the assignment being open-ended with minimal constraints. The limited number of keywords available from the assignment led to a narrow range of search terms in their input definitions, causing the groups to discover and select the same procedural, tool-related video information.*

In the case of the high-rise (21X3), data shows a distribution across three distinct strategies, indicating a different learning curve for the different groups. However, most groups rely on tool related information retrieval to make design decisions. At that point, groups can rely on tool knowledge without the need for information retrieval however there is still a high portion (43%) relying on tool related information to inform design decisions.

For the multi-functional building (22X3) , data illustrates a distribution across four different strategies indicating a different learning curve for the different groups. However, most groups rely on tool related information retrieval to make design decisions. The results are less pronounced than 21X3 however as stated before the D→←T can hide design drifts (→D←T) due to the class environment.

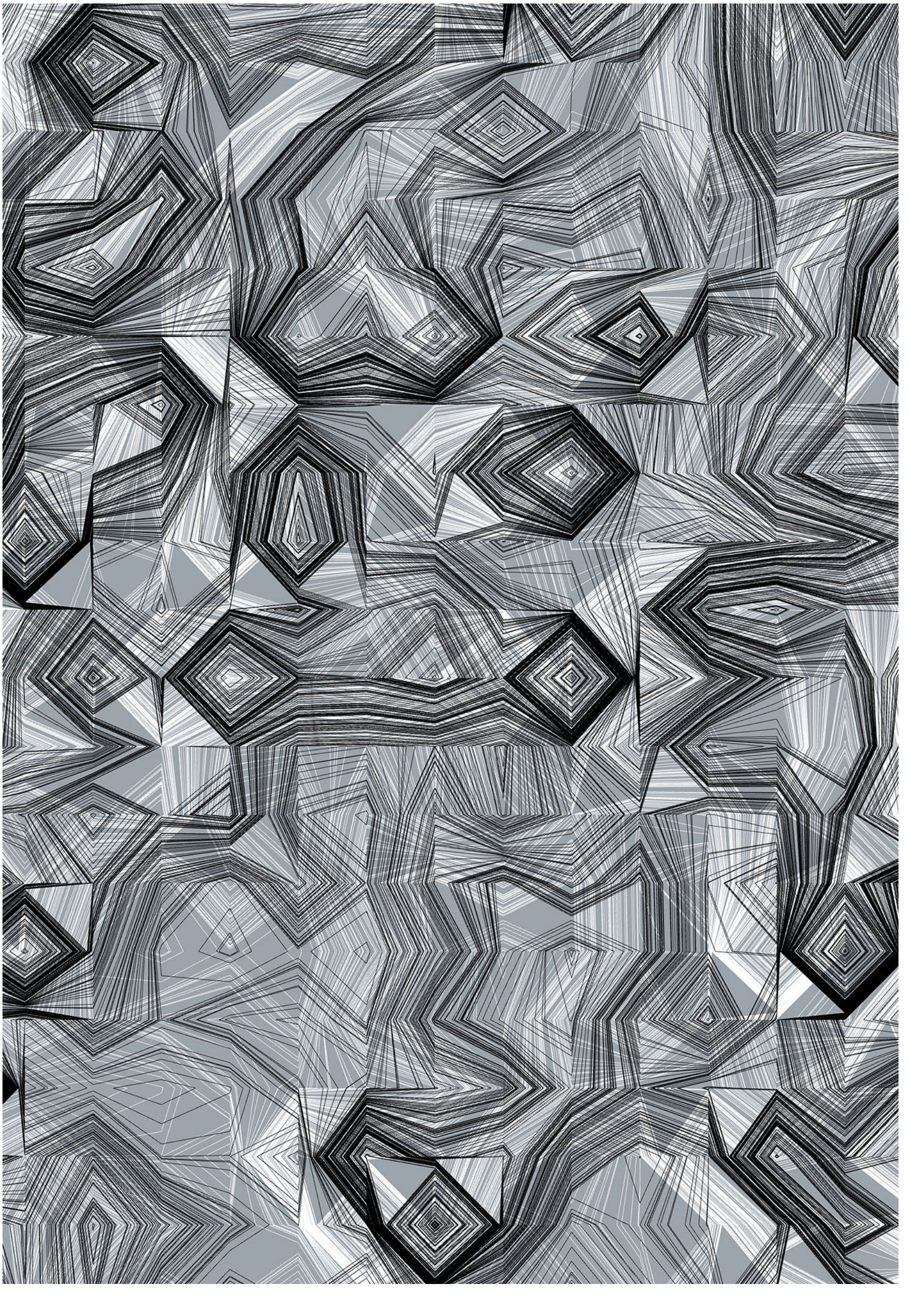


Figure 4.53: *Final result for 21X2B.*

Figure 4.54: *Final result for 22X2C.*

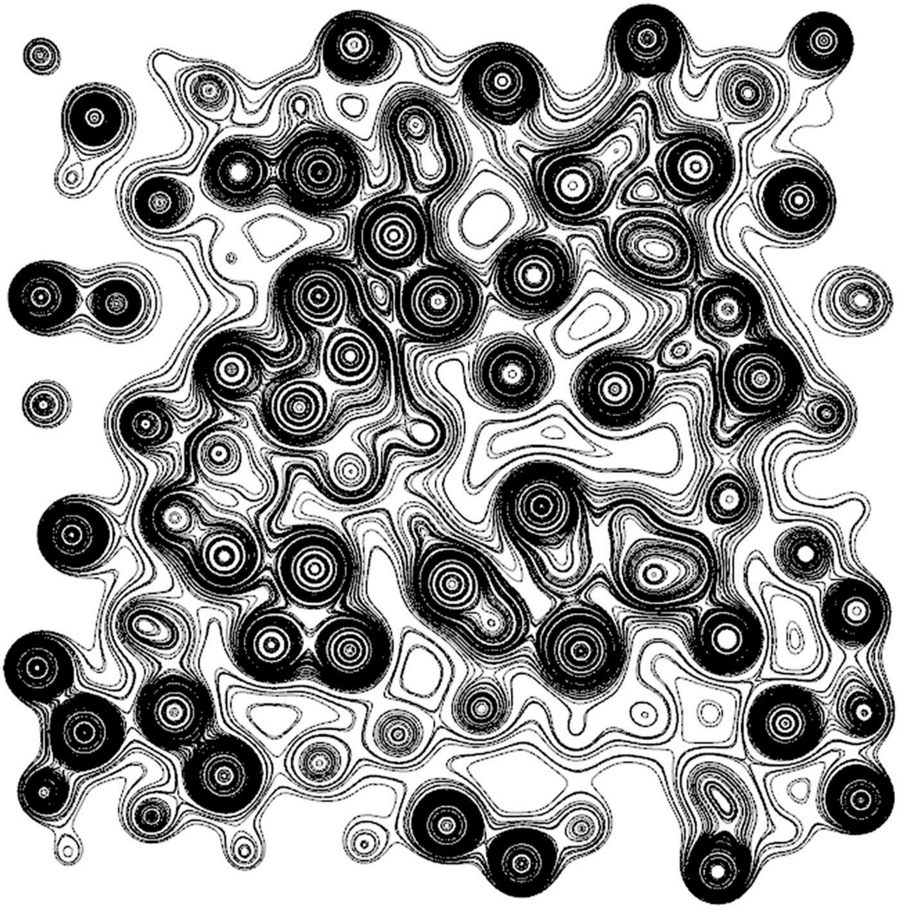


Figure 4.55: *Final result for 22X2G.*

4.3.5.2 Results overall

There is a pronounced preference for retrieving tool-related information, the distribution of strategies employed exhibited nuances between 2021 and 2022 (see Figure 4.56). This variation suggests that different teaching approaches can significantly influence students' methods of meeting learning objectives. A prime example of this is observed with the 22X2 assignment, which emerged distinctly as an outlier. Additionally, learning curves varied not just between different cohorts but also among individual students

2021	D	D→	→D	
T	0%	29%	0%	29%
←T	5%	33%	33%	71%
T←	0%	0%	0%	0%
	5%	62%	33%	

2022	D	D→	→D	
T	0%	5%	0%	5%
←T	5%	52%	38%	95%
T←	0%	0%	0%	0%
	5%	57%	38%	

ALL	D	D→	→D	
T	0%	17%	0%	17%
←T	5%	43%	36%	83%
T←	0%	0%	0%	0%
	5%	60%	36%	

Figure 4.56: *Distribution of search strategies on a 2 dimension matrix. Dimension 1 relates to design knowledge and dimension 2 relates to tool knowledge with or without expansion*

Regarding the use of tool related information retrieval (←T) consistently emerged as the preferred method aligning with the intended learning objectives. Conversely, UI exploration (T) was not frequently chosen likely due to its inherent constraints, particularly when working with complex and feature-rich tools like Grasshopper©.

Design development without information retrieval (D) occurred only once specifically in the third exercise suggesting a possible connection to usability concerns. The majority of design development was accompanied by information retrieval, which is consistent with findings from the literature review. However, distinguishing between design development through information retrieval (D→) and design shifts (→D) solely based on logs proved challenging, as students may be reluctant to admit copying tutorials and deriving their design from there.

Notably the occurrence of →D significantly increased starting from X2, indicating that students recognized the abundance of available information. This finding suggests that poor analogical reasoning influenced by information retrieval and the nature of the design problems, may have contributed to this trend. It is worth insisting that this approximation is likely underestimated and information retrieval may be stimulated by the inspiration derived from corresponding tool information as demonstrated by various references in the presentations.

Instances of T← were never observed. This is understandable since the course was focused on one specific tool however it's interesting to note that the use of other tools wasn't prohibited either.

Considering the learning objectives, the emphasis on information retrieval for expanding tool knowledge was generally successful. However, the shift towards →D, particularly in the context of design assignments, raises concerns. These findings underscore the impact of tool information retrieval on the design process and it is important to note that these numbers are likely underestimated. The results also provide valuable insights for course improvements, reducing biases, and establishing clear learning objectives for various design-related subjects with consideration of information retrieval activity. Furthermore, the complete absence of tool switch to fit the design intent indicates the difficulty of implementing such a process at the project scale, or at least within the scope of this class.

Overall, the results confirm that tool-related information retrieval for knowledge expansion noticeably impacts the design process. Figure 4.57 represents the design strategy distribution in relation to the model.

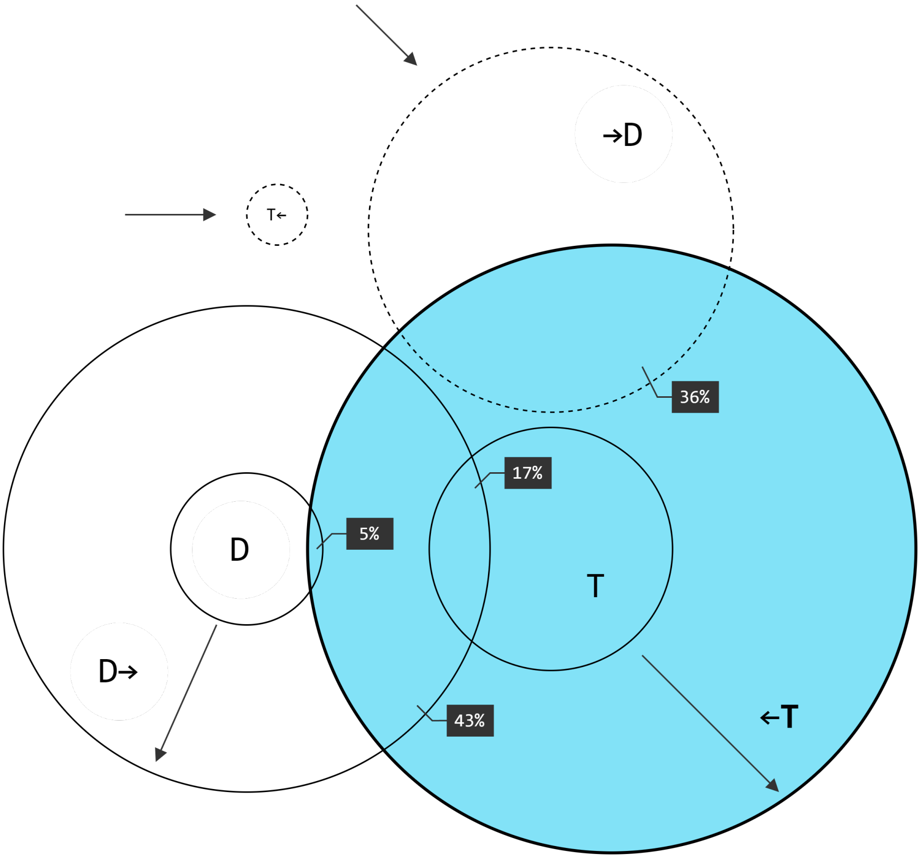


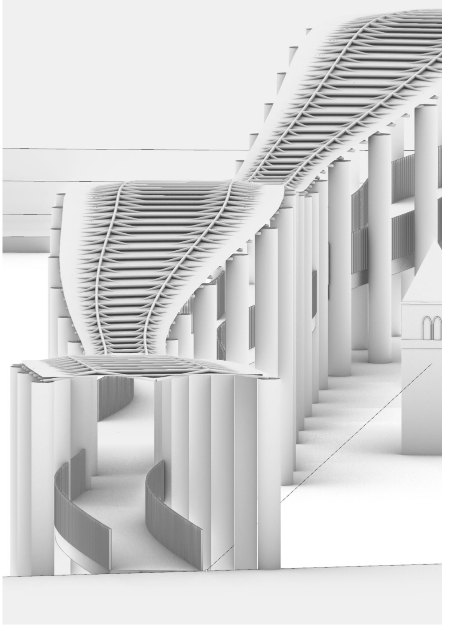
Figure 4.57: *Distribution of design strategies and corresponding affordance spaces. Tool-related information is accentuated due to its presence in all observed strategies. 5% of design strategies involve design prior knowledge in combination with expanded tool knowledge. 17% of design strategies involve expanded design knowledge with prior tool knowledge. 36% of design strategies involve a design shift due to information retrieval. 43% of design strategies involve the expansion of both design and tool knowledge. Ultimately the figure shows how the retrieval of tool related information plays an important role in the design process overall.*

FINAL RESULTS

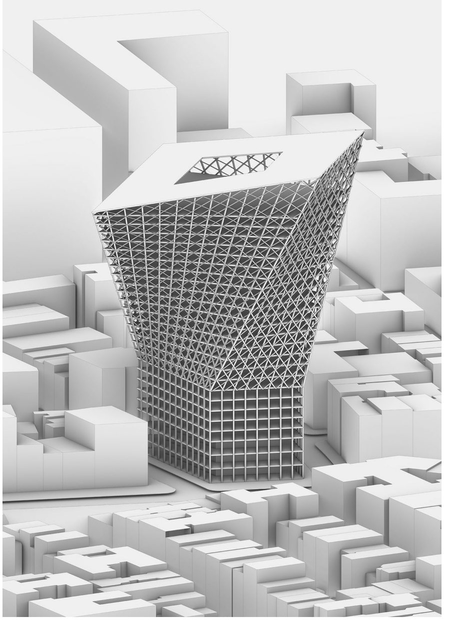
Following are all the final results for X1 X2 and X3 and for each group

2021
A

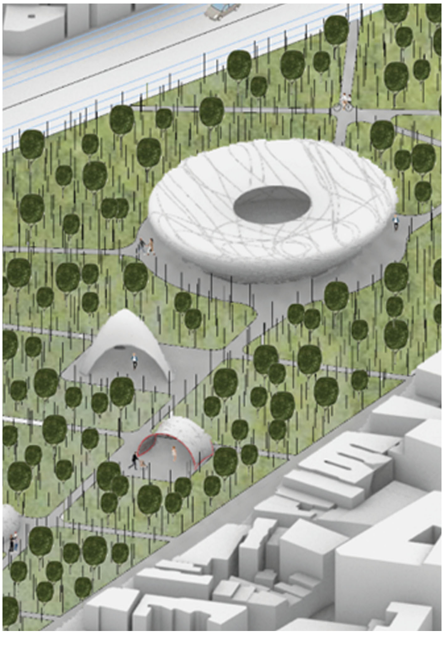
2021
B

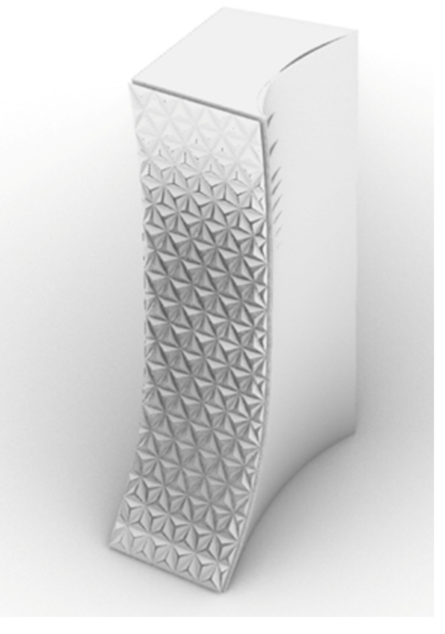


2021
C

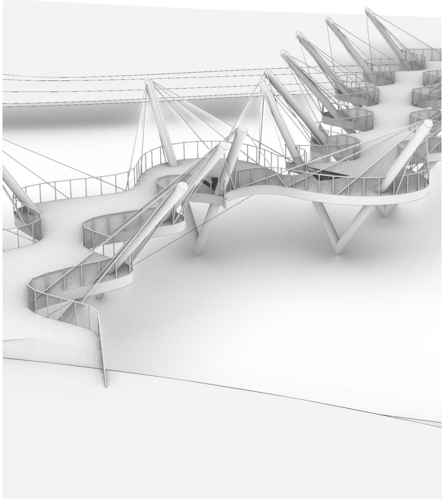


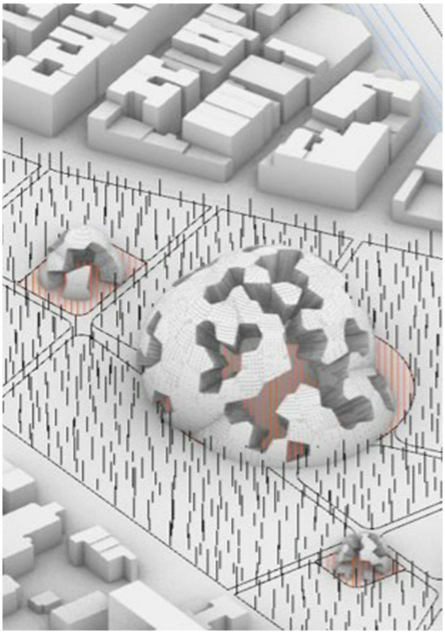
2021
D

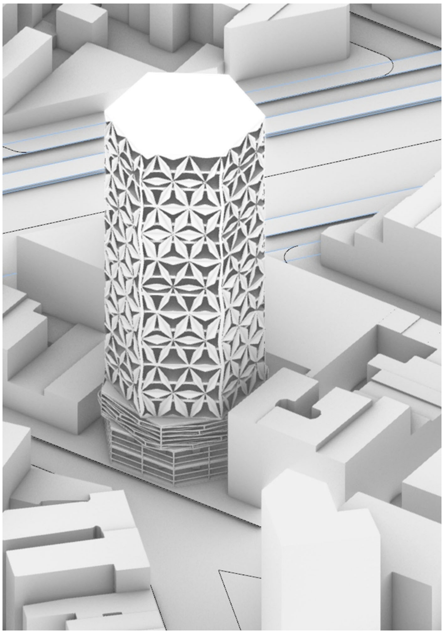




2021
E

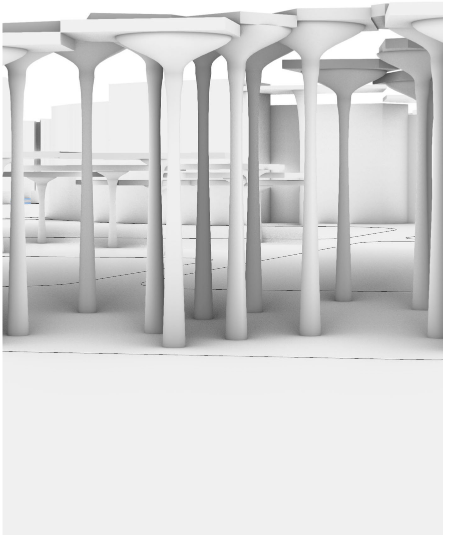


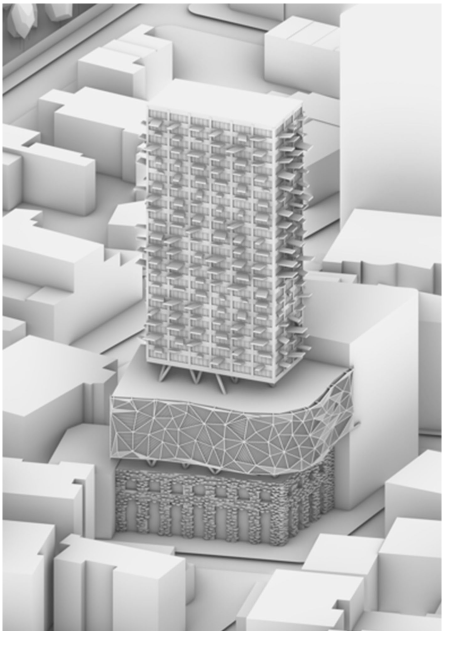




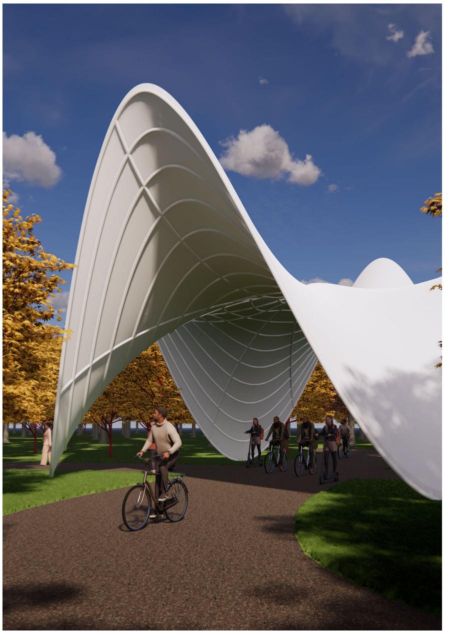
2021
F

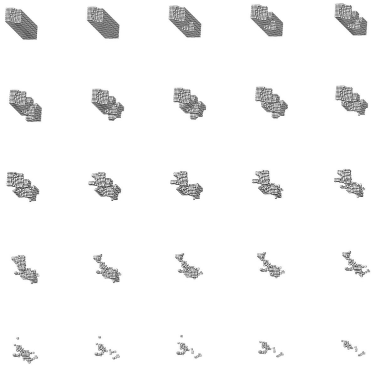
2021
G



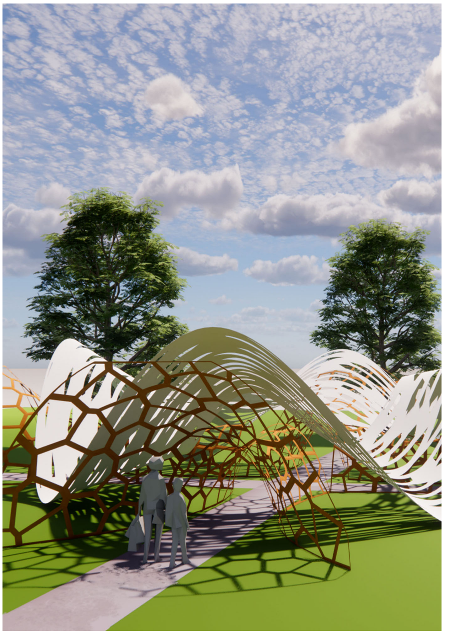


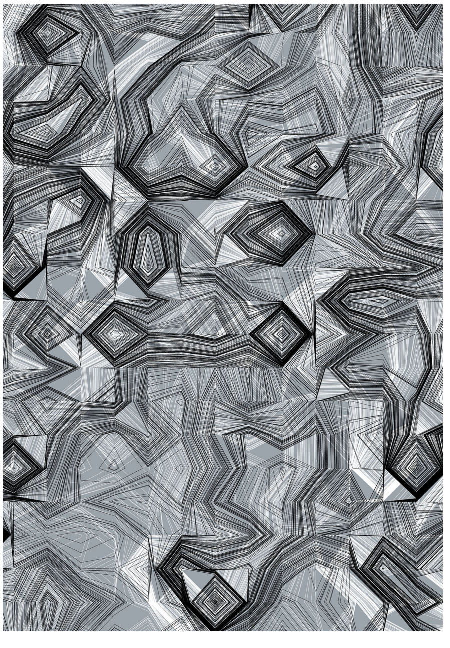
2022
A

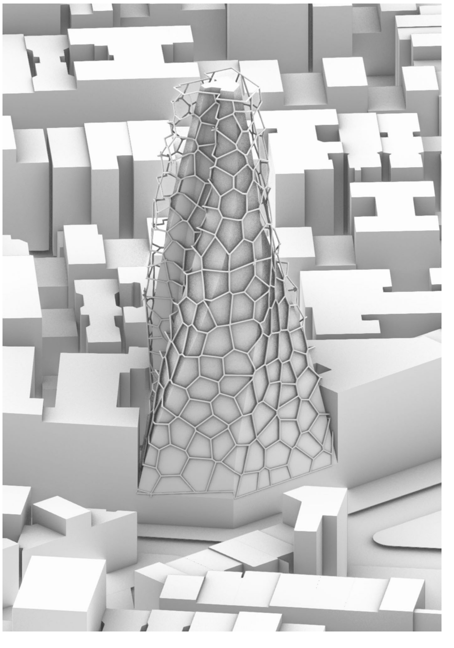




2022 B

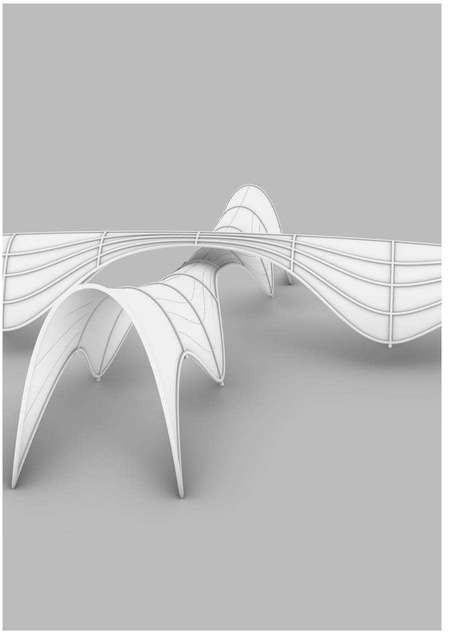


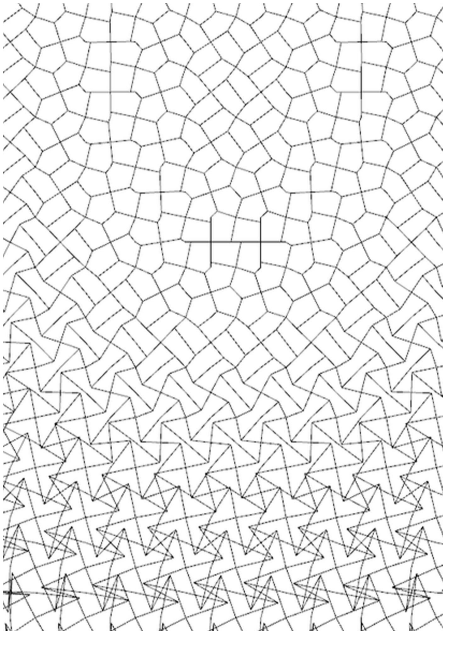


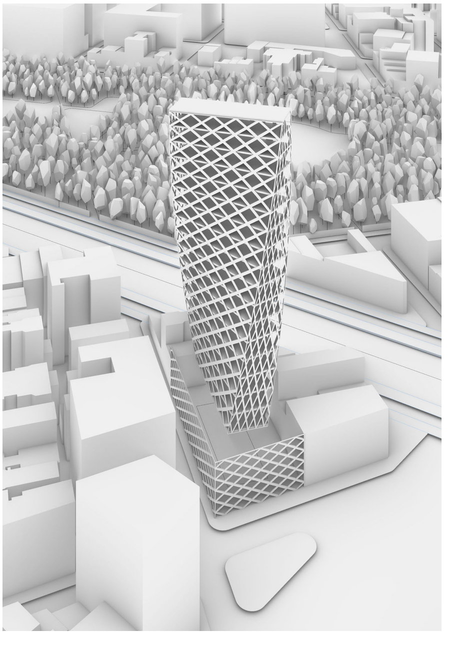


2022
C

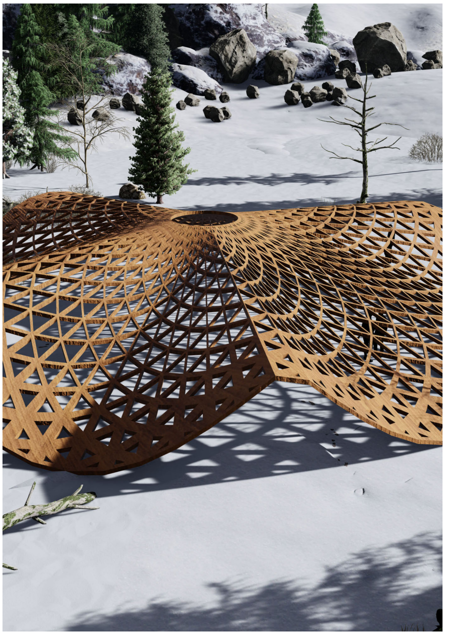
2022
D



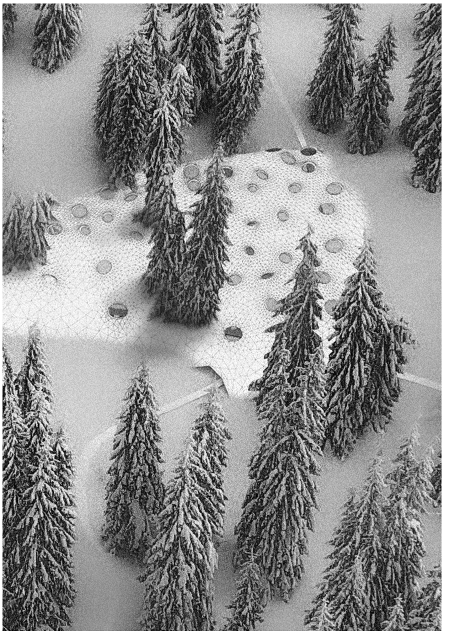


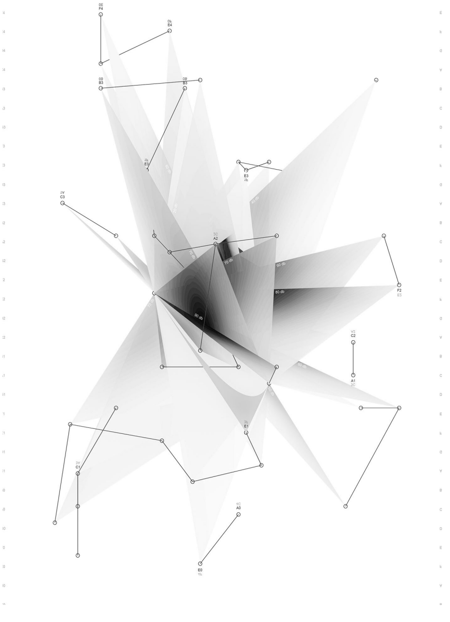


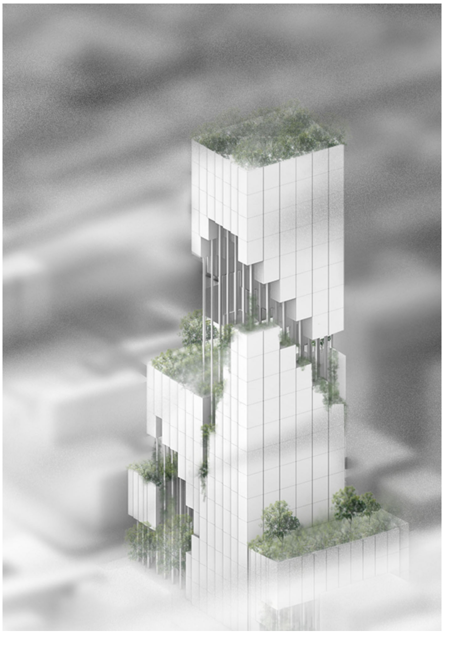
2022
E



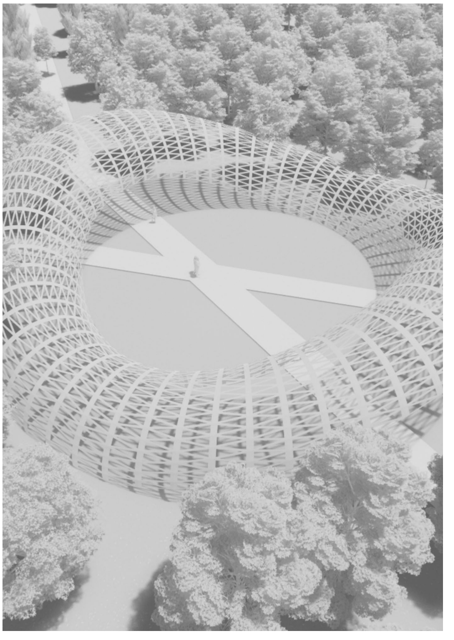
2022
F

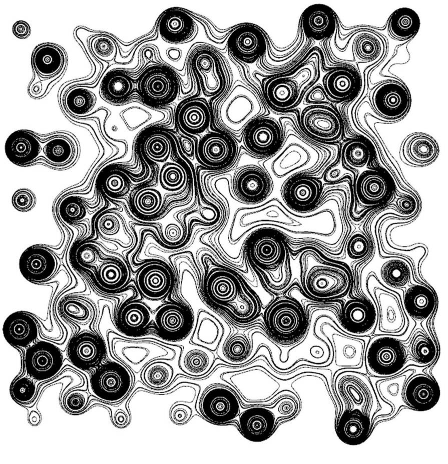






2022
G





5 Discussion

This chapter provides insight into the results derived from the systematic exploration of the conceptual framework using the design information model. The first section describes the model to situate different hypotheses and establish a foundation for the subsequent discussion regarding the nature of information, incorporating information type, source, and category to reflect the influence of tools on design strategies. The following sections address the questions articulated in the objectives, starting with the inclusion of tools within the conceptual framework. This section explores how tools act as catalysts for information retrieval, emphasizing their pivotal role in shaping design outcomes. Next, sources are examined to emphasize the relationship between information sources and types, and how this interplay shapes the architectural design process. The chapter then engages in a broader discussion on how information retrieval supports cognitive processes in architectural design through the reduction of cognitive load. Finally, the chapter concludes by identifying the limitations of this research, offering a critical assessment of the conceptual framework and its implications for future studies in design. Given recent advances in AI, additional perspectives are proposed to outline potential avenues for further exploration.

5.1 The Design Information² model

The conceptual framework and its corresponding model, developed throughout the literature review, form the foundation for understanding the results. This model builds upon the premise of Interactive Information Retrieval (IIR) that considers information retrieval as a learning activity, known as "Search as Learning," consequently suggesting aligning theoretical assumptions from IIR with architectural design processes. In particular, the "create" task, analogous to design, served as a basis for transferring empirical results and theoretical assumptions to architectural information retrieval. This concept enabled the extension of design theories based on the information-to-knowledge process.

The Concept-Knowledge theory was therefore expanded to the Concept-Information model by understanding how knowledge could be extended to support the concept space. To make the processes involved in the proposed Concept-Information model explicit, two additional frameworks were introduced. Function-Behavior-Structure (FBS) clarifies the concept domain as a series of design issues, with the structure S defined as the central design issue that serves as the foundation for knowledge expansion, placing it at the core of the model and linking the design and information domains. Given that the concept domain is now based on the more explicit FBS framework, the proposed model became the Design-Information model to avoid confusion.

The inspiration process characterizes the information-to-knowledge process, as it is specifically tailored to the design process. It depicts information retrieval into 3 processes, the definition of search input, the search strategy and the selection. It also introduces the fact that while information retrieval can be beneficial (inspiration) it is also vulnerable to design fixation. This realization brought to light the impact of recommender systems within search systems as a critical factor in shaping design outcomes.

When introducing the design concept, the property of generativity was considered. This concept is grounded in the premise of generating new knowledge, which is relevant to information retrieval because it implies that information retrieval should foster the development of design rather than merely provide a pre-existing solution. Furthermore, this focus on generativity resolves any ambiguity surrounding the concept of creativity by encompassing both ideation and the means to create a corresponding entity the structure S. This structure is indispensable, as it serves as a catalyst for information retrieval and a foundational trigger for design development through further reformulation (see Figure 5.1).

However, the generativity aspect necessitates the ability to produce a structure, which inherently involves the use of tools. In design studies, sketching is often the default tool in the early stages of design, but considering the information-rich context of contemporary design, the inclusion of tools beyond sketching is crucial. Empirical data in IIR revolves around the concept of complexity, and it's undeniable that tools, particularly digital ones, have become increasingly intricate. Parametric design environments, for instance, naturally exemplify this trend. Consequently, information is categorized into two main types: design-related I_D and tool-related information I_T. This categorization served as the basis for our initial research question, which explored whether the tool should be considered in assessing the impact of information retrieval on the architectural design process.

Given the consideration of the information-to-knowledge process, each category of information can be attributed its own knowledge space. Initially, the structure S existed solely within knowledge, but due to the principles of generativity and the necessity for synthesis, it needs to exist within both design knowledge and tool knowledge. To conceptualize this, the concept of affordance was used, specifically the subsystem model that depicts the affordance space at the intersection of both subsystems, design knowledge and tool knowledge. This affordance space represents the potential design landscape, aligning with the principles of generativity. By considering both knowledge domains simultaneously, the subsystem model effectively captures the way in which design and tool knowledge interact to expand the landscape of possibilities in architectural design.

Empirical results in Interactive Information Retrieval (IIR) rely on specific types of information as parameters. However, empirical studies in design lack a standardized taxonomy and instead use diverse categorizations that challenge comparability. To address this gap, the methodology incorporated a more comprehensive view of the nature of information through three dimensions.

The first dimension is information type, as used in IIR. The second dimension introduces the concept of information category, which integrates tools directly into the design process. While the impact of tools on architectural design is well-documented, their role in information retrieval remains underexplored in this context. The third dimension is the source of information, as is often considered in design studies. This last dimension offers a new perspective on framing information. To evaluate its impact, the information source was examined in relation to the information type, forming a comprehensive approach that aligns the building blocks of the framework with established empirical results.

Finally the model adresses effort. In design all issues are depicted as the result of cognitive processes as they require a certain cognitive effort. In inspiration effort is also seen as a driver for selection. Furthermore, recommender systems play a role in alleviating effort related to information retrieval. Tools are considered for their inherent complexity and the demands they might impose even though they are designed to alleviate effort in practice. However in this case it is hypothesized tools will actually interfere in information retrieval. Finally affordance adresses effort as cognitive affordance which excludes any action that is expected to exceed a certain threshold. To address and frame what seems to be a primary factor in search behaviors within the design process, the conceptual framework incorporates cognitive load as an definition of effort. Understanding how cognitive load is integrated into the results is crucial to comprehending the model's application in architectural design. Eventually it offers a wealth of empirical data to tap into for further research.

The foundation of the following discussion is anchored in two research questions concerning the nature of information. The information category is concerned with whether the information is directed towards tool or design issues, and informs on the validity of the proposition of integrating within the expanded design process proposed by the conceptual mode and ultimately the impact of tools in architectural design. The source of information is looked at in relation to information type as the type benefits from a theoretical foundation and pertains to cognitive effort while the methodology proposes the premise of a classification as the source does not have a shared theoretical foundation and is constantly evolving. The exploration seeks to understand their effects on the dynamic interplay between cognitive processes and information retrieval mechanisms, with a special focus on Parametric Design Environments (PDEs). These environments were chosen for several reasons. Their complexity and novelty to the experiment participants mirrored the scenario of an architect encountering new tools or software updates, creating a context that encouraged information retrieval, which was essential for this study. Moreover, PDEs are notable for their ability to seamlessly incorporate complex information, acting like sensitive measurement devices that reveal how the retrieval process unfolds and where it is absent. This setup allowed for an in-depth examination of situations where information retrieval was and was not used, offering valuable insights into its role in shaping the design process.

This chapter delves into how digital tools influence the design process and explores the nuanced effects of information retrieval, highlighting the role of recommender systems. It seeks to unravel the complexities of these interactions, discussing not only the role of tools in the design process but also examining how information retrieval mechanisms can both facilitate and complicate architectural design activities. Furthermore, it assesses the validity of the proposed model in capturing the impact of information retrieval on architectural design, aiming to shed light on the broader implications for the interaction between design knowledge and tools. While the results are extracted from a specific study context, they hint at the model's broader applicability. The strategies described are grounded in a more global theoretical foundation, ready for adaptation in diverse design settings. The proposed framework is intended to provide a robust theoretical base for exploring how the affordance space for generativity evolves, which is useful not only in the specific context of this study but also across varied design disciplines and potentially to professional environments.

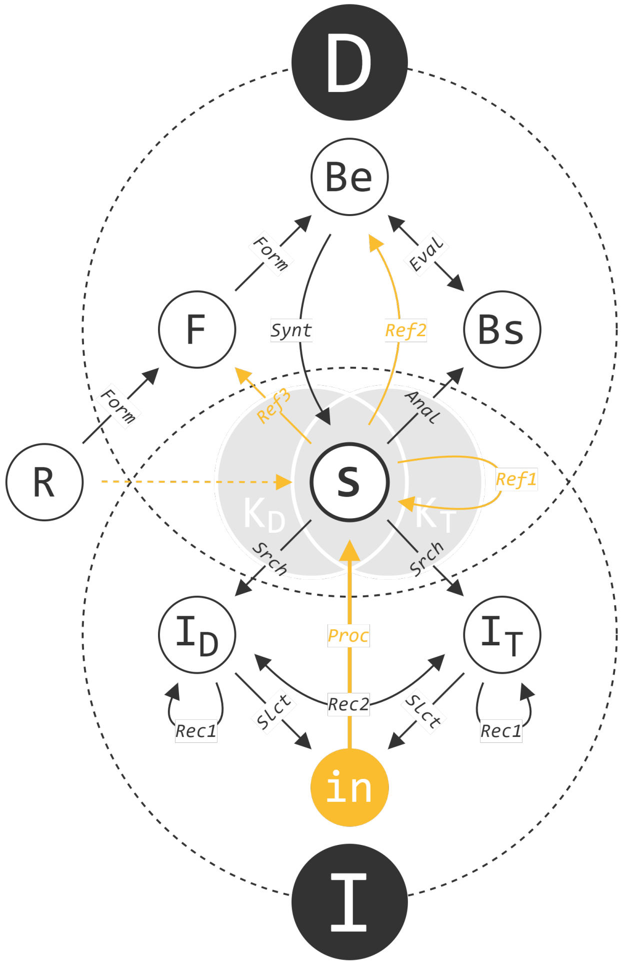


Figure 5.1: *The conceptual model. The model shows an arrow going from the requirements R directly to the structure to display how recommender systems can make alleviate the effort associated with formulation and synthesis. The model does not take documentation into account as the document is simply the last structure meaning there is no further reformulation as even document oriented structure can trigger reformulation albeit with less flexibility or at the cost of more effort.*

5.2 The tool as an information retrieval catalyst

Addressing the first question regarding the category of information and consequently the impact of tools through IR, the distinction between design-related information (I_D) and tool-related information (I_T) has proven insightful. I_T, in particular, plays a pivotal role in the design process, evidenced by its predominant use in the design strategies of students. The observed trend, while anticipated due to the nature of the course, indicates potential broader applicability beyond academic contexts, extending into professional environments. It is posited that this process is universal for individuals encountering a new tool. Parametric Design Environments (PDEs) are distinctive because they deviate from traditional modeling tools; however, this paradigm shift is not unique to PDEs alone. Similar transitions can be observed in other popular modeling software like 3dsMax© or Blender©, which are also parametric, grounded in explicit history, and support visual scripting. As shown in a previous study (Dissaux & Jancart, 2022), despite an initial reliance on prior knowledge, sustained engagement leads to a primary reliance on IR. This underscores the crucial role IR plays in navigating advanced tools and highlights the importance of IR in the design process, particularly concerning I_T.

In this context, the pervasive presence of I_T retrieval across all examined scenarios emphasizes its critical role, but its absence also stands out as a significant observation. Students compared the course's design process with their usual approach in design studios and noted a reduced reliance on I_T, attributing this to their familiarity with the tools. This suggests that the affordance space is constrained by the students' existing tool knowledge, which may limit design exploration to the bounds of usability. Similarly, in PDEs, I_D retrieval is shaped by the tool's knowledge space (K_T), which frames perceived architectural affordances and restricts design possibilities to prior knowledge. As K_D grows within K_T, it may reinforce the architect's sense of continuous flow (see Figure 5.2) similarly to sketching (Claeys, 2023). This interaction between design knowledge (K_D) and tool knowledge (K_T) reveals a cyclical reinforcement of procedural habits and architectural perceptions.

Sketching was traditionally viewed as an activity with unlimited usability and no constraints. With computational advancements, however, while sketching can indeed support computational and parametric thinking, it is often limited by technicalities. AI technology could bridge the gap between the intuitive freedom of sketching and the technical requirements of computational and parametric design. By facilitating the transformation of freehand sketches into computationally interpretable models, AI could greatly improve the usability of

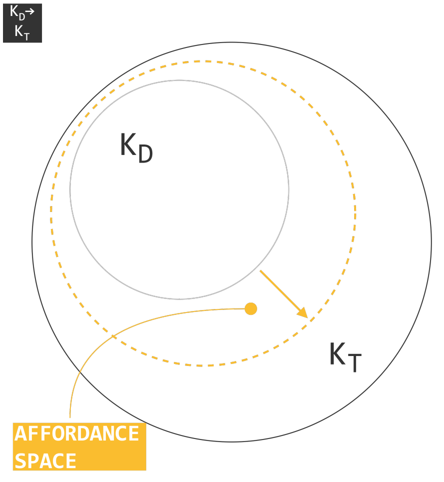


Figure 5.2: *Expansion of* K_D *within* K_T.

sketching in the digital design process. However, usability is highly personal: what one person finds intuitive and seamless may not be useful for another. Nevertheless, the absence of I_T in the process provides valuable data, making the information category dimension (I_D and I_T) increasingly relevant.

The impact of I_T retrieval on the design process varies widely. A significant portion of strategies incorporating I_T retrieval leads to a shift in design, highlighting its considerable influence (K_D • ¸¸K_T). However, this observation might be conservative and potentially underreported due to academic pressures. The most prevalent strategy observed involves expanding both K_D and K_T without an obvious preference for I_T-induced design shifts. This expansion happens through sketches, IR, or a combination of both, demonstrating the dynamic relationship between design and tool knowledge.

Interestingly, the process often entails a simultaneous expansion of K_T and K_D, with I_T retrieval sometimes serving almost as documentation as it might not lead to further reformulation. However, the lack of alignment between I_T and predefined structures suggests a potential loss of control over the design process. Furthermore, tool engagement frequently reveals new affordances that deviate from the original design intentions. This shift indicates a bias in search systems toward parametric design solutions, as seen in typical results like the "twisted tower" and "Voronois."

When K_T retrieval occurs immediately, it aligns with a solution-oriented design process focused on constructing PDE-based structures. This approach doesn't involve prior investment in formulating a structure outside of the PDEs. Instead, search inputs are defined by the assignment requirements and tool-specific descriptors like "parametric" or "Grasshopper©," enriching and guiding I_D to provide direction and inspiration. This can often lead to a focus on tool-specific typologies, where students find relevant images one day and tutorials for those designs the next.

Thus, the tool itself is already embedded in the initial formulation. Immediate I_T retrieval, which aims to create PDE-based structures, reflects a solution-oriented design process lacking initial tool knowledge (K_T). Search inputs are influenced by assignment demands and tool-specific terms, potentially leading to a narrower view of design. This emphasizes the complex interplay between design and tool knowledge, information retrieval, and the resulting architecture, as the tool's impact begins in the initial design phase.

5.3 Recipes for architecture

In exploring information sources within the design process, visual content emerges as the primary medium, consistent with previous studies (Lorenzo & López Chao, 2021; Makri & Warwick, 2010). This preference for visual information, especially when it serves as a preview for more detailed materials like videos or explicit parametric definitions, highlights the distinctive affordances visual stimuli offer in influencing design decisions.As Bresciani notes (2019), the impact of visual stimuli spans several dimensions. These include "structural restrictiveness," which illustrates how visuals can guide or limit design possibilities, and "outcome clarity," which shows the influence of perceived cognitive effort on decision-making based on empirical data in IIR (E. Alexander et al., 2015; Byström, 2002). Among the various forms of visual information, videos stand out as a significant yet underexplored resource in the design literature.

Videos, particularly in the context of parametric design environments (PDEs), play a crucial role. They differ from images, which primarily expand design knowledge (K_D), because videos often focus on tool knowledge (K_T) and typically appear as procedural information (I^P) in tutorials. Despite this, students use videos to obtain factual information (I^F) to expand K_T while also being submitted to conceptual design information (I_D^C). Due to the challenge of keyword formulation, videos are a more accessible source of I^F. The contextual I^P provided in tutorials helps bridge the gap caused by limited prior K_T.

Regarding the contribution of videos to K^C, it's important to insist that this pertains to design-specific K_D^C rather than tool-specific K_T^C. Video tutorials are often used as design references, guiding the expansion of design knowledge through I_T-focused queries. This observation challenges the initial model, which suggested an interactive relationship between categories of information (I_D and I_T). The unexpected realization that I_T could encompass I_D offers significant insight into their role as a reference, aligning with the scenario in Figure 5.3. This encapsulation implies that the expansion of K_D happens within the domain of I_T, mirroring the dynamics in Figure 5.2, where knowledge expansion takes place within K_T, or in this case, within I_T.

Figure 5.3 reveals the nuances of defining search inputs, where the use of tool-related terms like "Parametric" inherently embeds I_D within I_T. This raises concerns about possible limitations due to prior knowledge and how specific keywords influence tool usage. For those not familiar with PDEs, the specificity of "parametric" as a keyword could narrow the reference landscape, signaling a shift in tool knowledge. As Serriano notes (2003), the role of the tool in development includes selecting the most suitable tool for the given task.

Interestingly, the role of I_T retrieval in design development can expand K_D by

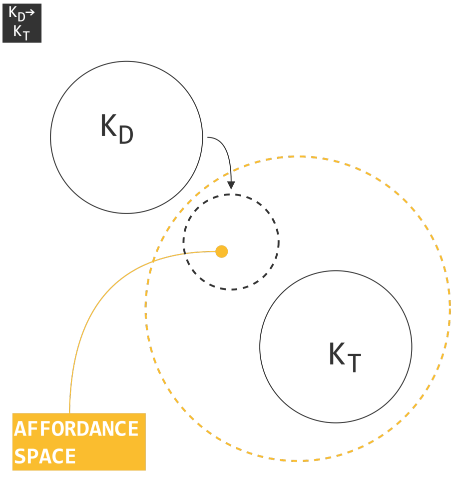


Figure 5.3: *The expansion of* K_D *exists within* I_T *as a solution oriented strategy.*

broadening perceived affordances. If K_D exists within K_T, expanding K_T can extend the range of perceived affordances. This underscores the importance of building K_T^C in parametric design education and practice, enabling more informed search input definitions. This reduces the risk of design shifts while providing access to a wider pool of information, freeing architects from relying on a single information source. These findings reinforce earlier assertions about the value of K^C in parametric design education (Vrouwe et al., 2020).

Contrary to empirical results in interactive information retrieval, people were not the preferred source of information (Byström, 2002). It's important to note that while the internet has evolved rapidly, so have strategies for information retrieval. The need for clear queries, often hampered by a lack of prior knowledge, along with diverse communication modalities, explain why students rely more on monitors in class rather than support chats, highlighting the procedural appeal of videos.

Group members present during the design process are often an underappreciated source of information. However, interviews suggest that the interactions among group members are more influential than students typically acknowledge. To communicate effectively, students use various methods to share ideas. Viewing the group as a cohesive unit, each mode of communication becomes a structural component of the collaborative process.

Sketches are a notable example, frequently used to communicate ideas but often left out of formal documentation. Their pivotal role in ideation and conceptualization stages positions them as a key tool for sharing ideas among team members, even if not directly acknowledged in design logs or interviews. Students have also reported sharing images with one another. Although not formally recorded, verbal exchanges may have played a role in clarifying and shaping search inputs.

In summary, the nature of information plays a crucial role in the design process. Understanding the division between design and tool-related knowledge is key to analyzing these behaviors, with videos heavily influencing design decisions, especially when considering recommendation systems (Tollon, 2021). Moreover, the uniformity in information retrieval across groups points to the influence of assignment formulation on information-seeking behavior, evidenced by semantic interference and abstraction barriers (Aish & Hanna, 2017). This consistency reveals biases in information retrieval systems and the effects of prior knowledge.

In the context of K_D within I_T, it appears as a less cognitively demanding process, shaping the expansion of design knowledge through I_T inquiries. This raises questions about the initial structure and the continuity perceived in sketches, despite possible discontinuities in synthesis (Claeys, 2023).

The ambiguity from previous research that the tool, in isolation, does not directly influence the design process is nuanced by the undeniable impact of user interface (UI) elements and prior tool knowledge on design choices. This influence, though not always overtly apparent in collected data, suggests that information affordance during information retrieval is inherently limited by statistical biases associated with the tool itself (Yu & Gero, 2015).

K_D's expansion through reformulation can occur independently of information retrieval, for instance through sketching, reminding that reformulation is not exclusively the outcome of information retrieval. Likewise, K_T may expand without direct information retrieval, but by relying on UI signifiers. This broader conceptualization of information retrieval includes inputs from sketches or UI elements, underscoring the subtler forms of recommendation present within a tool's UI, such as design cues suggested by the prominence of certain functions over others. These UI signifiers, much like the intentional design cues architects employ to influence user behavior in physical spaces, play a significant role in guiding design decisions.

This distinction is crucial because the notion of generativity is predicated on the expansion of knowledge. Behaviors indicative of a stagnation in design knowledge expansion coupled with a mere documentation of existing structures without further reformulation suggest a superficial integration of tool knowledge. Moreover, the acknowledgement of inherent discontinuities in synthesizing a structure supports Pallasmaa's (2012) contention that even the act of drafting, as distinct from sketching, constitutes an integral part of the design process. Thus, the documentation stage signifies the final synthesis of a structure, marking the cessation of K_D expansion. These considerations collectively affirm the tool's inevitable influence on the design process.

The relationship between sketches and information retrieval, particularly in determining whether sketches validate I_T or vice versa, remains ambiguous due to data granularity limitations. The analysis did not traditionally categorize sketching as a form of information retrieval, thus it has been included within the scope of K_D, explaining the observed prevalence of $K_D \rightarrow \leftarrow K_T$ interactions. Moving forward, it is imperative to discern between $K_D \rightarrow (I_T)$ and $K_D \rightarrow$(Sketch) as distinct iterations of S (structure) and to recognize the expansion of K_D as a result of these interactions, as conceptualized within the C-K theory framework (see Figure 5.4). This approach will better articulate the interplay between design knowledge expansion and tool interaction, providing clearer insights into the dynamics of the design process.

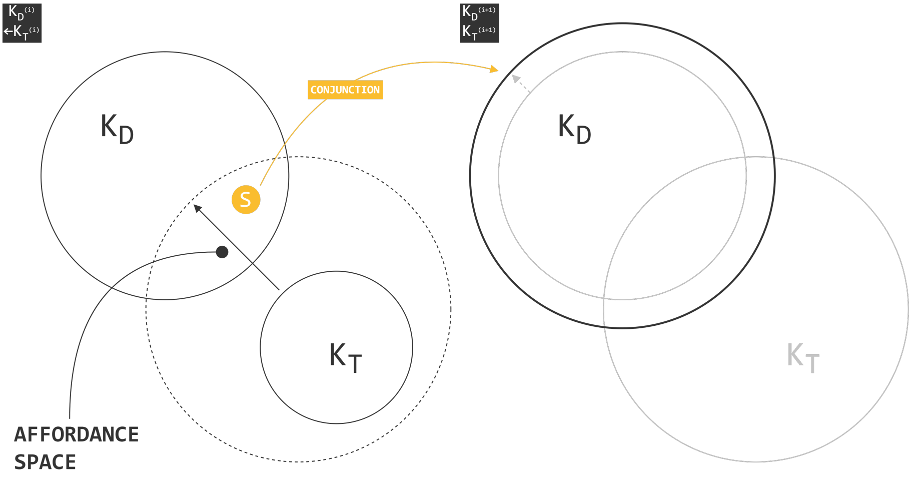


Figure 5.4: *Structure exists in the affordance space at iteration i of the design process. At i+1* K_D *is extended however the impact of* I_T *is not visible anymore.*

5.4 The support of cognitive processes with IIR

The concept of structure (S) has been implied to encapsulate or represent the definition of search inputs, consistent with its role across various contexts. Through the lens of affordance and complementarity, it's posited that S manifests uniquely at the intersection of design knowledge K_D and tool knowledge K_T, attributed to the principle of generativity. However, the nature of search inputs, akin to the distinctions between schematic and physical structures as outlined by Gero and McNeill (1998), does not inherently support knowledge expansion or prompt a reformulation process. This delineation implies that keywords, forming the structure of search inputs, are direct transpositions of expected behaviors (Be), lacking prior synthesis and serving merely as proxies for structures influenced by retrieved information.

The formulation of Be, incorporating assignment-specific keywords and tool-related terms, effectively reduces the cognitive load associated with formulation processes and synthesis, as depicted in Figure 5.5. This streamlined approach to defining search inputs may minimize the germane cognitive load, crucial for learning and design exploration, by leveraging recommender systems. These systems, by simplifying the definition of search inputs, mitigate the need for engaging in design-related cognitive processes, thus impacting the depth of the architectural design process.

The influence of recommender systems extends beyond cognitive load reduction; they also establish implicit connections between non-uniform architectural styles and parametric design environments. While these systems are designed to facilitate information retrieval, they can also constrain the designer's ability to explore beyond the algorithmically determined "relevant" content. Relevant has gained a special meaning within the information business as there is an incentive to being relevant nowadays (Bryant, 2020). This can lead to a homogenization of design outcomes, as designers may find themselves funneled towards solutions that are algorithmically favored rather than uniquely tailored to their specific design challenges. The convenience with which students can find relevant video tutorials using the same tools underscores these connections. Yet, this ease of access raises concerns about potential biases and the limitations it imposes on design exploration. The lure of easily accessible tutorials can inadvertently narrow the scope of exploration, as students might struggle to find resources that align with design ideas developed outside the predefined notions of parametric architecture facilitated by search systems.

Students' search strategies, favoring procedural information (I^P) over factual

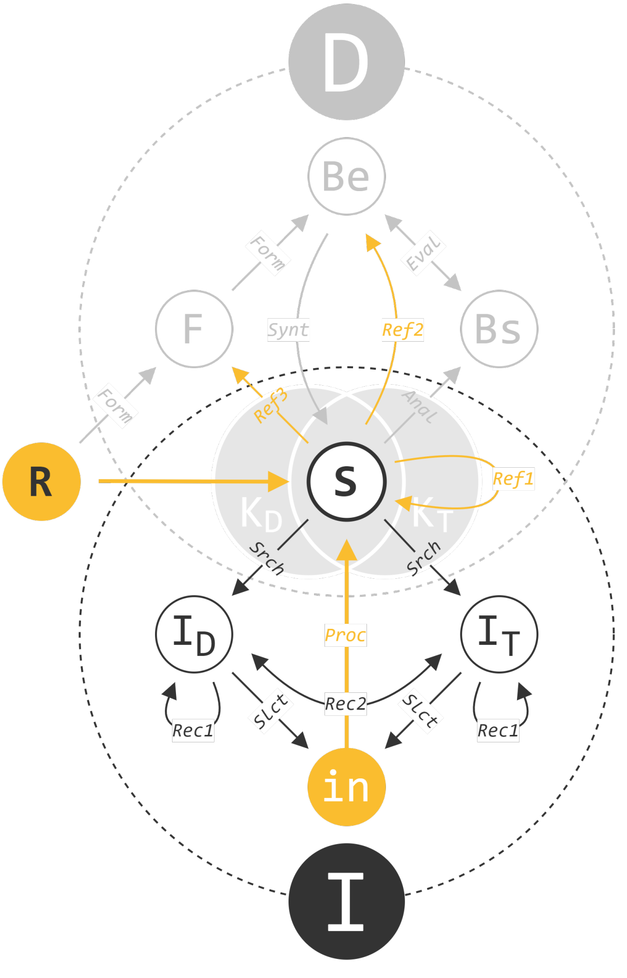


Figure 5.5: *Recommender systems allow for vague definition of search inputs therefore alleviating the need for design related cognitive processes going from Requirements R directly to a structure that is only meant for information retrieval.*

information (I^F) and conceptual information (I^C), reflect a prioritization of cognitive efficiency within the design process. This preference suggests that retrieving I^F requires a foundational K^C and deliberate formulation of search inputs, aligning with the concept of active search with purpose as described by Goncalves et al. (2016). In contrast, retrieving I^C, while seemingly more straightforward, necessitates analogical reasoning to adapt the information to the specific design context. The predominance of I^P, often conveyed through video content, is facilitated by recommender systems that implicitly guide the reformulation of search inquiries with minimal cognitive effort from the user (see Figure 5.6).

This scenario illustrates how recommender systems serve as a quasi-autonomous agent in the design process, offering a path of least resistance that may inadvertently constrain the design exploration by reinforcing existing knowledge structures without necessitating cognitive effort for reformulation. The tool-supported structure of S, therefore, not only simplifies the search process but also shapes the architectural design exploration in profound ways, potentially limiting the diversity and innovativeness of design outcomes.

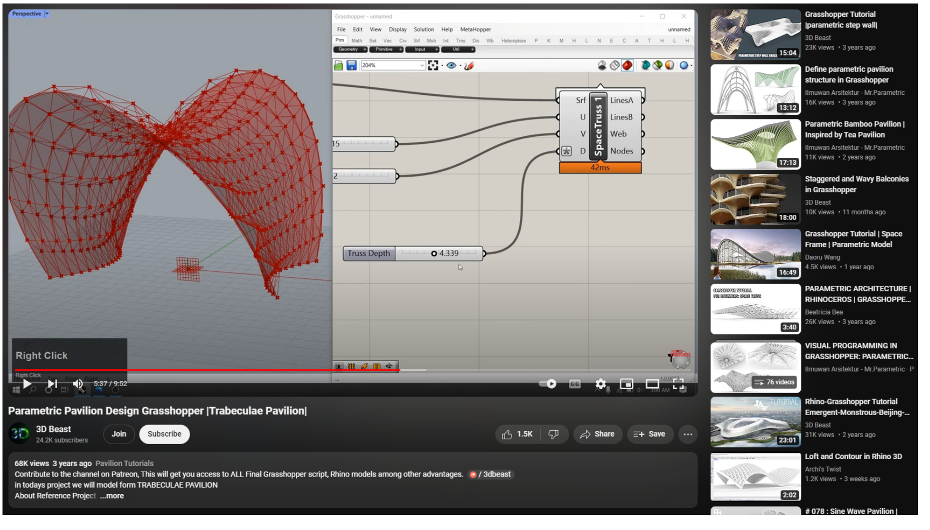


Figure 5.6: *Here is an example of the Youtube Interface proposing related videos based on prior search.*

In regard to images the approach to search definition is similar yet the information procured is inherently conceptual, offering semantically rich imagery that acts as a structural foundation for reformulation. Much like videos, images are subject to implicit reformulation through the influence of recommender systems. The use of tool-specific semantics, such as “parametric,” tends to yield results that are closely aligned with video content, effectively making images act as precursors or thumbnails for deeper explorations via tutorials (see Figure 5.7). An intriguing pattern emerged showing that the absence of reference imagery in the initial search stages led to a pronounced design shift, attributed to the difficulty in locating relevant tool information. This process results in the construction of a web-specific conceptual knowledge (K^C) around parametric architecture, inherently biased by the prevalent statistical norms of internet resources. Groups that bypassed initial image referencing in favor of direct tool-specific structuring found their outcomes more heavily influenced by the biases inherent to that tool’s ecosystem.

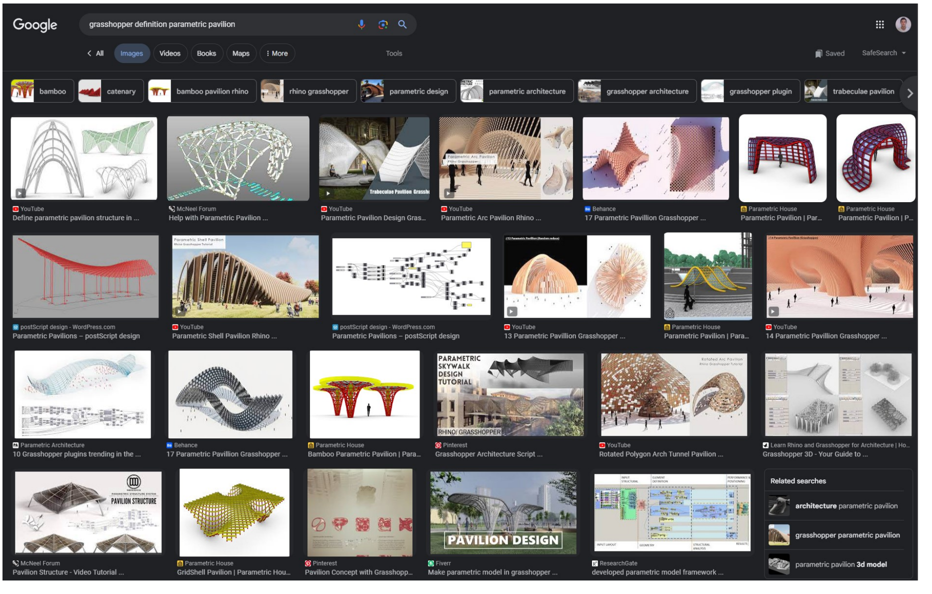


__Figure 5.7:__ Example of a Google© image search. Out of 24 images, 7 are thumbnails for video tutorials, 6 display visual script information, 8 indirect links to tutorials (primarily videos), and 1 connects to a download link for a specific script.

This observed behavior aligns with the findings of Goncalves et al. (2016), which discuss the dynamics of active random search facilitated by recommender systems. Yet, these systems can sometimes counteract intentional search strategies, particularly when students engage in active searches with specific objectives only to encounter unexpected, serendipitous findings, effectively transitioning their search from active to passive. Recommendations influence search strategies by introducing new ideas or pathways that might not have been initially considered.

The selection criteria within the analysis remains somewhat vague due to data granularity issues. However, relevance often guides the selection process, especially when students use assignment-specific terms as search keywords. The procedural aspect of information significantly influences selection. The recognition factor is crucial for students aiming to realize their designs within the tool's capabilities, with the visual similarity of information prompting significant reformulations. However, it can be argued that relevance is the actual driver but in regards to the tool rather than the design description. The same can be said for reliability as videos are chosen for the reliability of their procedural information. Selection criteria should therefore be distinguished in regard to information category. Curiosity, though challenging to quantify, is notably driven by the novelty of the tool and its parametric features, serving both as a motivator and a means of verification for suitability within parametric design environments (PDEs) (e.g: if it looks unfamiliar it's probably relevant for PDEs). The criteria for curiosity also extend to the perceived effort involved in engaging with the information, which is increasingly mitigated by the procedural information embedded in tutorials. Moreover the information is tool based and not necessarily architecture based so the question of analogical distance gets nuanced as distance does not relate to more effort but a risk for fixation due to lack of context. Moreover it should be concerned with both K_D and K_T expansion (e.g: Introducing music as inspiration for a graphic display can perhaps be seen as analogically distant however the tool has a function for the music to serve as form generator).

Ultimately, regardless of the selection driver, effort is a critical parameter in the information search process, and its intensity can vary significantly based on the nature of the information. For instance, a curiosity-driven search might be more effortlessly conducted through procedural visual information. On the other hand, the recognition driver, when applied to an image lacking context or requiring specific tool-based synthesis knowledge, may present a more challenging task.

The minimization of cognitive load emerges as a recurring theme across all processes. The initial search for references simplifies the formulation and synthesis phases, while recommender systems streamline the search effort, and tutorial videos reduce the need for extensive reformulation. This approach to reducing cognitive load may seem to diminish generativity, suggesting a shift from creative tasks to application-oriented tasks within the use of PDEs. Unlike conventional design processes that require architects to reinterpret images through their tools, PDEs demand a nuanced understanding of parametric principles, making effortless integration through these environments even more compelling.

This exploration through digital resources underscores the transformative potential of information retrieval in the design process, not just as a preliminary step but as a continuous, integral element. This necessitates an educational paradigm shift that equips students not only with the technical proficiencies required for digital tool use but also with the cognitive strategies to leverage information in architectural design.

Given these findings, previous assertions about information searching in architecture can be reinterpreted. Goodey and Matthew's work on information preferences in the office translates into the ability to rely on more visible information and recommendations (Goodey & Matthew, 1971). The preference for concise and visual information remains valid (MacKinder, 1983), especially with today's capability to quickly sift through large amounts of data. Powell and Nichols (1982) suggested that information retrieval (IR) occurred mainly in response to major design problems and relied heavily on prior knowledge. However, the rise of computational tools and new complexities has made tool-related information searches integral to solving design challenges.

Traditional tools still pose IR challenges due to different concerns. However, the internet has transformed architects' behavior. Students, at least, haven't reported failures in finding "the right kind of information" or being overwhelmed by "too much information" (Rhodes, 1998). Contrary to Rhodes' findings (1998), students didn't prefer magazines and journals, likely because of the complexities introduced by digital tools that significantly influenced search behaviors towards I_T. Additionally printed material is slow to find, often limited to the curation of the library, plus is associated with physical constraints

The evolution of search processes, particularly with recommender systems, has mitigated earlier challenges linked to interactive information retrieval (IIR) and the internet (Elliott, 2001). Bennett (2006) observed that architecture students showed early interest in accidental discoveries but also noted that experienced architects relied heavily on prior knowledge.

The need to integrate Information Retrieval (IR) into architectural education, first emphasized nearly 50 years ago by Snow (Snow, 1975), is even more critical today. These findings contribute to the growing body of literature advocating for improved digital literacy, which is widely recognized as essential. More broadly, they also support the push for increased metacognitive knowledge in educational curricula. This narrow focus on tool mastery, coupled with inadequate engagement with supportive information, highlights a vulnerability: the challenge of navigating vast, uncurated information pools. As per cognitive load theory, it is crucial to equip students with the skills necessary to independently navigate their learning processes, especially when dealing with complex, evolving computational tools (de Bruin & van Merriënboer, 2017; Sithole et al., 2017; Van Merriënboer & Sluijsmans, 2009). The absence of prior experience and a reduction in supportive information can diminish critical engagement with the process, allowing external sources to exert greater influence on design decisions.

The complexity of PDEs necessitates a new approach to integrating supportive information, challenging the findings of previous studies that employed more controlled experimental settings. This raises questions about the suitability of experimental designs and analytical methods in computational design and cognition research.

5.5 Limits of research design

Parametric Design Environments

Parametric Design Environments were selected for this study due to their alignment with the complexities, rapid evolution, and computational approaches characteristic of the digital era in architecture. The susceptibility of PDEs to information retrieval, facilitated by the direct transfer capabilities of visual scripting, makes them particularly suitable for this research. Additionally, while the usability of PDEs is not limitless, it significantly surpasses that of traditional direct modeling methods. This enhanced usability is not solely a product of user interface design but is also bolstered by functionalities that continue to evolve through community contributions.

The broader usability of PDEs, compared to traditional direct modeling methods, allows this study to supposedly better isolate the impact of information retrieval more effectively. This hypothesis is supported by the fact that information retrieval is seldom mentioned when studying the impact of tools in architectural design. Indeed, traditional direct modeling environments might confine designers to the usability constraints of their user interfaces. In contrast, like PDEs, sketches or maquettes do not have clear defined usability limitations either however, they do not necessarily require tool related information retrieval as it's not affected by technological advancements (except for hybrid methods).

While PDEs are pivotal to this study and exemplify a specific range of behaviors, recognizing the broader implications of different design environments remains a limitation of the current research. This acknowledgment highlights an opportunity for further investigation into how various environments influence information retrieval and design outcomes.

Data collection

It is essential to recognize the limitations of our sample. The study primarily involved architecture students, whose behaviors and strategies might not fully mirror those of practicing professionals. Despite the partial quantitative approach, the small sample size and the variation in variables across different academic years inhibit our ability to perform statistical analysis that could be generalized to a broader population. Consequently, while the results offer valuable insights into architectural design education, they should be interpreted with caution when considering their relevance to professional practices. Further research with a more diverse and larger sample is critical to extend these insights into different professional development stages.

The questionnaire produced mixed results. Regarding information types, there was either a significant lack of awareness about search strategies, emphasizing the need for better digital literacy in education, or the students didn't fully understand the distinctions despite detailed explanations and the presence of an assistant to answer questions. Additionally, two students mentioned that the 1-to-5 scale was too restrictive. Despite this, the high variability in responses suggests the need for either larger sample sizes or more individualized consideration.

This study sheds light on how architecture students manage cognitive load while working in parametric design environments (PDEs). However, it also cautions against broad generalizations due to the sample's limited size and scope. It assumes a uniform cognitive profile among students, failing to account for individual differences like motivation, which can affect working memory capacity (Grogan et al., 2021).

Regarding the interview, it's important to note that the students, due to their position, inherently aimed to please with their responses. Moreover, the answers often lacked detail, suggesting that some of the additional questions may have hinted at specific responses. The inconsistency between the process and the content analyzed afterward reveals a lack of awareness of the impact of information retrieval. However, using the logs for support during the interview could have provided more detailed answers.

When analyzing the logs, it's evident that students tend to prioritize visually appealing presentations over an accurate representation of their design process. Some groups even adjusted the provided template to better suit their presentations. This points to the need to consider how presentation-focused expectations influence the content of the logs.

Thurlow and Ford (2018) observed that the emphasis on polished presentations in higher education can alter students' engagement with the design process, potentially leading to sketch inhibition. The results align with this concept, as sketches were rarely seen and mainly supported information searches, especially for images that were then used to guide design development. The scarcity of sketches in this information-rich environment suggests a heightened reliance on digital information sources. However, the PowerPoint-based log format may not fully capture sketching activities, potentially underrepresenting this aspect of the students' design process. Moreover, the requirement to document the process through PowerPoint may have influenced the affordance space itself.

Ultimately, the information shared by students reflects what they consider relevant to their design process. The rest often emerges during interviews when specific questions are asked, such as about the use of sketches that were initially omitted and considered unimportant. Minor factual information retrievals also tend to go unreported, tempering concerns about a lack of cognitive investment in prior planning. Students may not feel compelled to report every Google©

search they conducted.

Conceptual Model

The behavior of the structure Bs and related processes, such as analysis and evaluation, are rarely discussed. However, information retrieval may play a role in the analysis process by helping evaluate whether the structure meets expected behaviors. In this case, the design depth was limited to visual resemblance, which occurred unconsciously. No student explicitly stated that they assessed the structure against expected behaviors (though this changed when generative AI was considered). Future research should explore this aspect further, potentially incorporating it as an information dimension, where for example tool-related information is utilized for verification and thus perhaps solely for analysis.

Students were required to conduct complex solar analyses to achieve specific performance criteria through simulation and optimization, but the relevant information was provided in class for the sake of the course. Previous experiments indicated that students often abandoned searches for such technical details, aligning with research on online education suggesting that more effort is needed for technical design aspects in autonomous learning situations (Yu et al., 2022). Due to time constraints, this aspect was not further explored; however, the model could serve as a basis for future investigations.

The structure can be understood as an image, but questions arise when a student assembles a collection of internet pictures and presents it as a design structure. An individual picture may not qualify as a structure since it doesn't align with generativity and doesn't produce new knowledge. However, curating a collection of selected images can lead to new insights and facilitate knowledge creation. Kerne and Koh (2007) explored combining visual elements to form composition spaces (see Figure 5.8). One of their examples nearly conceptualized an "almost iPhone" (before its release) by merging images of iPods and cameras, although no prototype was created; they simply gathered existing images to illustrate an idea. Still, this arrangement promoted knowledge synthesis through conceptual action, leaving a gray area around the boundary of ideation within generativity.

The structure may appear at the sketch level, where it summarizes the composition. Confusion may arise from overlapping theoretical frameworks, but the resulting conceptual framework can help clarify these boundaries. This methodology uses parametric tools to support the structure, treating sketches and selected information as intermediary structures. This approach sidesteps potential ambiguities of generative AI in image creation. However, rapid technological advancements suggest comprehensive BIM model generators could soon become available, reducing the reliance on tool-specific structures.

This comprehensive approach yields novel insights, setting the stage for future,

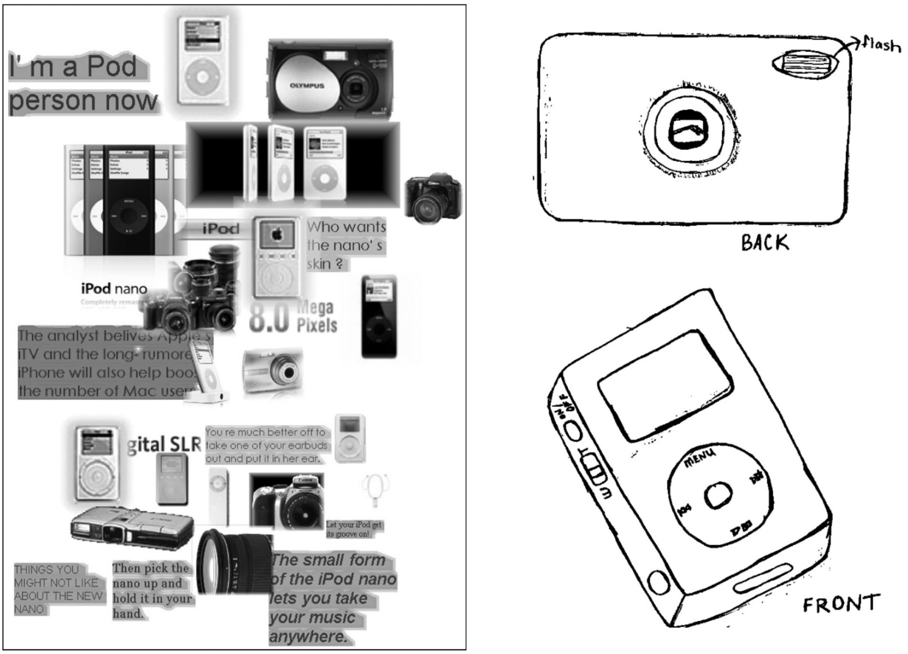


Figure 5.8: *Prior work collection for the iPod Camera project, developed as a composition using combinFormation, is displayed on the left. On the right is a sketch of the same project, illustrating the iPod Camera concept (Kerne & Koh, 2007).*

more detailed investigations that can delve into specific aspects of the model, potentially offering a more nuanced understanding of the interplay between cognitive processes, information retrieval, and design tool usage in both architectural practice and education.

5.6 Note on AI

In the exploration of the design process, the conceptual model proposed highlights the need to delve into the potential implications and future research opportunities that Artificial Intelligence (AI) could introduce into architectural design and information retrieval. AI's versatility offers opportunities to revise synthesis, formulation, reformulation, documentation, evaluation, analysis, and also as a revolutionary search system. Each of these roles not only enhances but also challenges traditional design methodologies, suggesting a fertile ground for further investigation.

AI transcends conventional search systems by enabling direct queries for generating structures across multiple media (text, images, audio, or video). For instance, text-to-image capabilities allow designers to design a house by outlining specific issues and constraints, showcasing AI's potential to directly translate conceptual ideas into tangible representations or structures. The representation is almost generative by nature compared to the use of an internet image.

AI's role extends to problem definition, where nuanced family or work-life scenarios can shape the design requirements of a home. This adaptability in understanding and integrating complex human needs into the design process exemplifies AI's capability to navigate and articulate the multifaceted nature of architectural design. Thus, while AI can synthesize solutions, it can also provide problem definitions.

AI aids in the reformulation process in multiple ways: from generating visual representations of described structures to assisting in keyword generation for refined searches. Its meta-cognitive abilities can sharpen the focus and direction of the design process, enabling a more iterative and dynamic development of design concepts.

AI's application in documentation, as seen in tools like Veras© for Revit©, streamlines the rendering of final models, reducing the cognitive and technical load on architects. Renders not only serve as the culmination of the design process but can also inspire further reformulation, showcasing AI's role in both concluding and inspiring design iterations. If documentation is considered here instead of synthesis, it is simply because of its hidden potential that might eventually revise the role of documentation.

Beyond creation and documentation, AI might offer the gap towards complex technicalities for the evaluation and analysis of designs, incorporating a range of criteria from environmental impact to user experience. This facilitates a more informed and comprehensive approach to architectural decision-making.

Distinguishing itself from traditional search engines, AI's capacity for multimodal input and its potential in refining recommendation systems start a new era in information retrieval. By supporting keyword definition and possibly redefining search aims beyond mere factual information acquisition, AI could significantly influence architects' search behavior and criteria for selection. The shift towards AI-assisted selection could mitigate personal biases, although it introduces the challenge of navigating the biases inherent within AI systems themselves.

As AI reshapes the landscape of architectural design, identifying where architects add the most value becomes crucial. The conceptual model provides a framework for understanding the cognitive processes involved in architectural design and perhaps identifying the ones that are most beneficial, suggesting that the future of architectural design lies not just in the adoption of advanced tools but in the synergistic integration of human and AI capabilities. This integration may well position architecture as a distinctive field of design, characterized by a unique blend of technology and human insight.

Future research should aim to dissect these implications further, exploring how AI can be harnessed to enhance the design process without diminishing the architect's role. The goal is to forge a partnership where AI serves as an extension of the architect's capabilities.

6 Conclusion

This chapter provides a comprehensive summary of how information retrieval impacts architectural design, based on the study's primary aim. It reflects on how the findings align with the conceptual framework and hypotheses, and sets the stage for future research by summarizing key insights and addressing broader implications. The chapter is organized around the conceptual framework and its design information model, which address three key research questions: the role of tools in information retrieval, the significance of information sources, and the applicability of cognitive load theory in understanding retrieval strategies and their influence on design outcomes. Summarized answers to these questions, drawn from the discussion, affirm the framework's relevance to both practice and education. The conclusion also explores the framework's potential evolution and versatility across different tools and populations and suggests its applicability in understanding the emerging impact of artificial intelligence on architectural design.

6.1 Introduction to conclusion

The primary aim of this research is to investigate the impact of information retrieval during the early stages of architectural design. The thesis accomplishes this by developing a conceptual framework to explore the nuances of information retrieval in early stages of design, and takes into account how architects engage with tools as part of their information retrieval. It provides a structured approach to examine the interplay between design, tools and information and the resulting cognitive strategies employed by architects.

The conceptual framework has leveraged different theories models and concepts based on the foundation of interactive information retrieval and the premise of searching as learning processing information into knowledge for design activity. Within this theoretical background, retrieval strategies are based on 2 dimensions. The first being the type of retrieval task in this case a create task as it relates to the design activity. The second dimension is related to the information retrieved to accomplish that task, more specifically its type. Research in information retrieval in design however do not rely on a similar framework so the information parameter had to be broaden. First the model considers the tool and consequently information as either design related or tool related defining the information category. Secondly research in information retrieval in design or inspiration does not offer any framing regarding information besides origin and modality, thus information source means to integrate and offer a classification. Those 3 dimensions of information are consolidated as the information nature. Eventually as are all theories leveraged design decisions and by extension information retrieval are governed by effort which is conceptualized as cognitive load.

This framework is then applied through the specific case of parametric design and architecture students. This focus on Parametric design environments is driven by their complexity and the unique demands they place on information processing and decision-making in design tasks. Furthermore, the participants had no previous experience with PDEs which fostered retrieval. By focusing on architecture students operating within PDEs, the study aims to reveal patterns and strategies in information retrieval that could potentially indicate broader trends in architectural practice when architects are confronted with a new tool or a major update, although further research is necessary to confirm this applicability. To do so, the experiment design used a mixed approach using questionnaires and interviews to expose information retrieval strategies of graduate students in architecture. The participants had no previous experience with PDEs which fostered retrieval.

The central hypothesis of this study posits that due to the complexities of parametric design, novices will heavily rely on information retrieval, which will subsequently guide design decisions. The research thus answers 3 questions. The first is concerned with the consideration of the tool within the expanded design process. Tool-related information is hypothesized to influence the design process, such as the reformulation of design concepts by the application of cognitive load saving strategies.

The second question is related to the nature of information, exploring whether cognitive strategies observed in relation to information types in "create" tasks in interactive information retrieval research can be extended to the broader nature of information, particularly its source. Finally, can the resulting strategies that shape how novices use information to guide their design processes and their impact can be related to cognitive load and as such should instructional effects from cognitive load be considered in teaching digital literacy in architecture.

6.2 Summary of Findings

6.2.1 The tool's impact

The consideration of tools within the design process plays a critical role, with tool-related information significantly influencing the design trajectory. The distinction between design-related information and tool-related information is crucial for understanding how tools shape design strategies. Tool-related information plays a pivotal role, as students frequently rely on it during the design process. Although this reliance is anticipated due to the course structure, it should be extended to professional contexts. When encountering new tools, individuals universally engage in a similar process that involves a heavy reliance on information retrieval, although further research is needed to confirm this applicability in professional settings.

Parametric Design Environments stand apart from traditional modeling tools, yet a similar shift can be observed with other computationally oriented softwares. Despite an initial dependence on prior knowledge, sustained engagement leads to a primary reliance on information retrieval, underlining its importance in navigating complex tools. The absence of tool-related information retrieval however, can constrain the design process, limiting students to their existing knowledge base. This directly affects their design exploration. Conversely, design-related information retrieval is influenced by tool knowledge, which frames the perceived affordances and restricts design possibilities. As design knowledge expands within the framework of tool knowledge, procedural habits and architectural perceptions reinforce the sense of continuous flow. Future research should consider AI-related technology as it could bridge the gap between the intuitive freedom of sketching and the technical requirements of computational design, but the usability of tools remains personal and subjective.

Eventually, tool-related information retrieval significantly impacts the design process, often resulting in a shift in design concepts through mental-saving strategies. The strategies involving tool-related information retrieval frequently lead to the expansion of both design and tool knowledge, demonstrating the dynamic relationship between the two. However, the lack of alignment between tool-related information and predefined structures can potentially cause a loss of control over the design process, as new affordances emerge that deviate from the original intentions.

In immediate tool-related information retrieval aimed at constructing structures based on parametric design environments, the approach often focuses on solutions within assignment requirements and tool-specific terms like "parametric" or "Grasshopper©." This shapes initial design structures, embedding the tool's influence from the beginning. The complex interplay between design and tool knowledge, information retrieval, and architectural outcomes reveals the considerable impact of tools on the expanded design process. Tool-related information, therefore, guides the reformulation of design concepts through strategic application of mental-saving strategies, leading to dynamic shifts and reinforcing the influence of tools on architecture.

Focusing on parametric design environments (PDEs) and architecture students, the framework revealed a nuanced spectrum of information retrieval patterns. The complexity of parametric tools necessitated significant reliance on tool-related information to guide design decisions. The framework however aims to remain adaptable to other design tools, acknowledging that both excess and deficiency in information retrieval can influence design processes. While the immediate focus is on parametric design environments, the conceptual model developed is intended to be applicable to various design settings involving different tools. This adaptability suggests that the framework is well-suited to explore diverse approaches to design that require varying degrees of information retrieval related to both design and tool usage. Future research should investigate the applicability of this framework to other tools and design situations to fully understand its versatility

6.2.2 Information nature

Visual information is the preferred medium, often serving as a preview for detailed resources like videos or explicit parametric definitions. Visual stimuli influence design decisions by offering both "structural restrictiveness," which limits or guides possibilities, and "outcome clarity," reducing cognitive effort in decision-making. Videos, underexplored in design literature, appear crucial in parametric design environments. They provide procedural information, mainly through tutorials that bridge the gap between limited tool information and practical application. Videos not only convey factual information but also help expand design knowledge by embedding design-related insights within tool knowledge. This observation challenges the initial model, which suggested an interactive relationship between design and tool knowledge categories. Instead, design related knowledge expands within tool related knowledge, meaning that increasing familiarity with tools broadens perceived design affordances.

The research highlights the critical nature of information, emphasizing the division between design and tool-related knowledge. Uniform retrieval strategies reveal biases in the information retrieval system, with semantic interference and abstraction barriers influencing behavior. The study also suggests that tool knowledge can be expanded through user interface (UI) elements, where intentional design cues prioritize some functions over others, subtly guiding the decision-making process.

6.2.3 Cognitive load

Cognitive load has been seen as a practical way to frame effort within the design information process. The principles of cognitive load help elucidate retrieval strategies and eventually the impact of information retrieval on the design process

The formulation of search inputs relies on assignment-specific keywords and tool-related terms, which reduce cognitive load during the search process. Recommender systems streamline search inputs, significantly reducing the cognitive effort required to locate relevant information. However, this ease of access can also limit exploration, as algorithmic biases guide designers toward popular, preselected solutions rather than encouraging unique, innovative approaches.

Recommender systems influence design beyond reducing cognitive load by establishing implicit connections between different architectural styles and parametric design environments (PDEs). While these systems ease information retrieval, they can also lead to the homogenization of design outcomes by funneling designers into algorithmically determined, "relevant" content. This is especially notable in the context of video tutorials, where the convenience of accessible resources often narrows the scope of exploration, limiting students to ideas within predefined notions of parametric architecture.

Students typically prioritize procedural information (procedural information) over factual (factual information) and conceptual (conceptual information) information, favoring cognitive efficiency in their searches. Procedural information is more accessible through videos, often supported by recommender systems that guide search inquiries with minimal effort. This minimizes the germane cognitive load required for active learning and reformulation, potentially constraining the design process by reinforcing existing structures.

The visual similarity in search results also drives reformulation, while relevance often guides selection. Curiosity, challenging to quantify, is driven by tool novelty and parametric features, and it is both a motivator and a verification method. Ultimately, curiosity-driven searches are conducted with procedural visual information, while recognition requires deliberate synthesis and can present a challenging task when context is lacking.

Reducing cognitive load is a consistent theme throughout the search process. Early searches streamline formulation and synthesis, recommender systems reduce search effort and the need for reformulation. However, these strategies might shift tasks from design exploration to more application-oriented tasks. Unlike traditional design processes requiring reinterpretation of images through tools, PDEs demand nuanced understanding of parametric principles, making information integration even more critical.

6.3 Final Words and Future Research Directions

The transformative impact of information retrieval shapes the design process as a continuous, integral element. This shift necessitates a new educational approach to equip students with cognitive strategies to leverage information effectively. The findings reinforce the importance of improving digital literacy and metacognitive knowledge in education to help students navigate the vast and uncurated information available online.

Moreover, previous empirical studies may need to adapt to the complexities of computational design and cognition research. Architectural education should incorporate digital literacy to help students critically engage with their learning processes, especially when using complex computational tools. To improve digital literacy and metacognitive skills, architecture programs should consider incorporating courses that teach efficient information retrieval strategies and emphasize the application of cognitive load theory in design decision-making. Such courses would equip students to manage the overwhelming amount of digital information. Without prior experience or supportive information, students are at greater risk of external influences shaping their design decisions, underscoring the need for new research approaches.

The findings align with previous research in leveraged theories and concepts, further supporting the conceptual framework's relevance. Additionally, they suggest the use of empirical data from those research field leveraged for the construction of this framework to serve as data for further research. By leveraging the insights derived from the conceptual model, this study aims to stimulate questions and offer a base for future investigations. It is anticipated that this conceptual framework will not only thrive on but also necessitate critical feedback and scholarly discourse for its evolution, adaptation and validation.

Beyond its theoretical contributions, the framework also holds practical potential for broader applications. In the context of architectural education, it has proven effective in isolating specific behaviors, enabling the use of these insights to inform the planning of learning objectives with a focus on enhancing information retrieval skills. This practical application underscores the framework's utility in educational settings, preparing students more effectively for professional challenges. However, the practical applications for practitioners are yet to be explored, suggesting a rich area for future research to examine how these theoretical constructs can be operationalized in professional practice. Thus, this work is positioned not as a conclusion but as a catalyst for continued exploration and discussion. This thesis provides a foundational base for future research into the intricate relationship between information retrieval and architectural design.

Ultimately, this thesis aims to provide a foundational basis for future research into information retrieval in architectural design. It seeks to contribute to a deeper understanding of how information retrieval, or the lack thereof, shapes design outcomes, thereby informing both education and practices. Considering how fast software tools evolve and are created nowadays, architects are bound to rely on external information to keep up with their expertise. This phenomenon is accentuated in new complex computational tools such as parametric design environments. By leveraging the insights derived from our model, this study aims to stimulate questions and offer a base for future investigations. It is anticipated that this conceptual framework will not only thrive on but also necessitate critical feedback and scholarly discourse for its evolution and adaptation. Thus, this work is positioned not as a conclusion but as a catalyst for continued exploration and discussion. The journey to comprehend the intricate interplay between technology and architectural design is ongoing.

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