A Critique of Craftsmanship in Computational Design Practices

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Since its early manifestations in ancient civilizations, craftsmanship has always been a fundamental aspect of human ingenuity. Today, the integration of digital tools and computational methods has been introducing new possibilities for the craft process. From this perspective, this study aims to explore and understand the multifaceted nature of craftsmanship in contemporary computational design practices. To do so, the study first provides an overview of craftsmanship, scrutinizing its historical roots, transformations during industrialization, and its enduring relevance in the digital era. Then, a cognitive framework is proposed to understand the process of craft, emphasizing the rhythm of knowledge production, the interplay of problem-solving and problem-finding, and the concept of slow time in skill development. Through the lens of this framework, the main characteristics of craftsmanship in computational design practices are interpreted as openness, nonlinearity, and complexity. The study also highlights the role of tool-making and interdisciplinary thinking in enhancing craftsmanship in computational design practices. Nevertheless, the study critiques computational design practices that prioritize efficiency and functionality over exploratory and reflective processes, which may undermine the potential essence of craftsmanship.

Keywords: Craftsmanship, Cognition, Computational Design, Generative Systems, Digital tools.

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Hesaplamalı Tasarım Pratiklerinde Zanaatkarlığın Eleştirisi

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Antik uygarlıklardaki erken tezahürlerinden bu yana, zanaatkarlık her zaman insan yaratıcılığının temel bir unsuru olmuştur. Günümüzde dijital araçlar ve hesaplamalı yöntemlerinin entegrasyonu, zanaat süreci için yeni olanaklar sunmaktadır. Bu bakış açısıyla, bu çalışma, çağdaş hesaplamalı tasarım pratiklerinde zanaatkarlığın çok yönlü doğasını keşfetmeyi ve anlamayı amaçlamaktadır. Bunun yapmak için, çalışma ilk olarak zanaatkarlığın tarihsel kökenlerini, sanayileşme sürecindeki dönüşümlerini ve dijital çağdaki kalıcı önemini inceleyerek bir genel bakış sunar. Ardından, çalışmada, zanaat sürecini anlamak için, bilgi üretiminin ritmini, problem çözme ve problem bulma arasındaki etkileşimi ve beceri gelişiminde yavaş zaman kavramını vurgulayan bilişsel bir çerçeve önerilmektedir. Bu çerçeveden yola çıkarak, hesaplamalı tasarım pratiklerindeki zanaatkarlığın ana özellikleri açıklık, doğrusallık olmama ve karmaşıklık olarak yorumlanmaktadır. Çalışma ayrıca, hesaplamalı tasarım pratiklerinde zanaatkarlığı geliştirmede araç yapımının ve disiplinler arası düşünmenin rolünü vurgulamaktadır. Bununla birlikte, çalışmada verimlilik ve işlevselliği keşfedici ve yansıtıcı süreçlerin önüne koyan hesaplamalı tasarım uygulamaları eleştirilmekte ve bu durumun zanaatkarlığın potansiyel özünü zayıflatabileceği belirtilmektedir.

Anahtar Kelimeler: Zanaatkarlık, Biliş, Hesaplamalı Tasarım, Üretken Sistemler, Dijital araçlar.

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1. INTRODUCTION

From its early manifestations in ancient civilizations to its adaptation in the digital age, craftsmanship has been a fundamental aspect of human ingenuity. In its broadest terms, craftsmanship encompasses not only the creation of physical artifacts but also the processes of refining skills, problematization, and profound engagement with materials, tools, media, and techniques (Sennett, 2008). Today, the integration of digital tools and computational methodologies has been redefining how craftspeople approach their work, introducing new possibilities for the process of craft. It is important to understand craftsmanship in computational design practices to ensure that new technologies enhance creative processes. The recent literature mainly focuses on developing pedagogies for digital craftsmanship (Cheatle & Jackson, 2023; Song, 2022; Tyler-Wood, 2022), integrating computational methodologies with traditional craft (Devendorf et al., 2023; Melnyk, 2020; Torres et al., 2016), implementing traditional crafts in the context of digital fabrication (Hansen, 2021; Shi et al., 2019; Van Der Veen et al., 2019), and situating computational design within craftsmanship (Noel et al., 2021). Although these studies provide valuable insights into digital craftsmanship by mainly examining the contributions of computational tools and methodologies, they often do not distinguish craftsmanship from mere technical proficiency in computational design. Hence, there is a lack of understanding regarding the specific characteristics that constitute craftsmanship in computational design. Understanding these characteristics means being able to recognize whether craftsmanship lacks or exists in computational design practices. Such understanding can also advance the field by stimulating more critical and reflective computational design practices that push the boundaries of creativity.

From this perspective, the main purpose of this study is to understand the multifaceted nature of craftsmanship in computational design practices by exploring characteristics that distinguish it from technical proficiency. To do so, the study first provides an overview of craftsmanship by scrutinizing its historical roots, transformations during industrialization, and its enduring relevance in the current digital age. It then explains the process of craft by composing a cognitive framework. Along with this framework and relevant examples from the literature, the study delves into the key characteristics of craftsmanship encountered in computational design practices. At last, the lack of craftsmanship in computational design is discussed to address the counter point of view. According to Niedderer and Townsend (2014, p. 626), contemporary craft is almost always defined through what it is not rather than what it is. Here, from another perspective, this study prefers to approach craft in computational design through how it is and how it is not.

2. HISTORICAL CONTEXT AND DEFINITION OF CRAFTSMANSHIP

Defining craftsmanship is a seemingly simple task. Yet, as Adamson (2018) asserts, it must be done in an open-ended manner by accepting its versatility and cultural logic. Only then, we can draw connections across different disciplines and craft activities without reserving or restricting them. Since prehistoric times, humanity has always been interested in crafting tools and artifacts. Throughout history, craftspeople have been shaping cultures and influencing daily life by blending artistic skill with practical utility.[1] However, the attitude towards craftspeople and their positions in society varied over time and culture. Although craftspeople remained in control of their crafts and tools until the Industrial Revolution, the introduction of mass production through new manufacturing processes and machinery reduced the reliance on traditional craftsmanship (see Greenhalgh, 1987/2010). At the time, while craftsmanship praised expertise, effort, and material, mass production was promoting practicality, disposability, and deliberate obsolescence by reducing the material into a commodity or a resource (Risatti, 2007, pp. 194-205). In this regard, mass production has flooded the world with things and impacted traditional conceptions about craft, production, value, and scale, which used to be closely tied to human labor and abilities. This situation led to the Arts and Crafts movement emphasizing the value of handmade design objects and the crafter's societal role (Greenhalgh, 1987/2010). Key figures in the Arts and Crafts movement, such as William Morris and John Ruskin, criticized the dehumanizing aspects of factory labor and the superficiality of mass-produced goods. Morris (1888/2018), in

[1] One of the earliest showcases of respect toward craftsmanship appears in the 20th Homeric hymn that celebrates the master deity of craftspeople Hephaestus for advancing human civilization from a primitive state by bringing the knowledge of crafts to humanity, ensuring a prosperous and peaceful life (Hesiod, 1914, p. 447). In Archaic Greece, craftsmanship was a deeply developed, valued, and respected field, where it was integrated into daily life, economy, social norms, culture, and politics.

particular, advocated for a return to high-quality, artisanal design, Ruskin (1853/2018) emphasized the moral and aesthetic superiority of handcrafted objects. They believed that craftsmanship should be celebrated not only for its functionality but also for its ability to reflect the values and creativity of its maker.

Here, it is important to distinguish that the major issue was not necessarily machinery or technology itself, but rather the shift to mass production methods and the way these were implemented during the industrialization. Masly produced products became uniform because of the standardized processes on production lines. The production process was broken down into simple repetitive tasks, increasing efficiency but reducing individual craftsmanship. Factory workers became machine operators, performing particular tasks within a production line, rather than acquiring a different set of skills. Now again, this does not mean that technological advancements in machinery inherently threaten traditional crafts work. The actual impact depends on the specific ways these technologies are implemented in large-scale production processes. In fact, technological developments and the "new" can nourish crafts simply depending on how they are adopted. For instance, modern craft-based movements in the twenty-first century, such as Do-It-Yourself or Maker culture, utilize advanced technologies to enhance creativity, skill, and craftsmanship, not diminish it (Kuznetsov & Paulos, 2010; Nascimento & Pólvora, 2018). These movements embrace technology and machinery, using tools like CNC machines, 3D printers, and laser cutters to create unique and personalized products. It is then possible to combine traditional craft skills with new tools, which demonstrates that technology can coexist with and even support craftsmanship. New technologies provide craftspeople with new tools, media, and ways to perform their craft (e.g., Hansen, 2021; Tamke et al., 2017); therefore, changes in technology and tools force craftspeople to rethink and re-explore their craft.

In the digital age of today, craft remains a fundamental part of human culture, evolving with technological advancements, integrating digital tools into traditional practices, adapting to societal changes, and maintaining a unique cultural identity. McCullough (1996) claims that digital technology not only offers new techniques and tools for crafting but can also become the basis of a medium – the digital medium. To him, craft is the application of personal knowledge and habitual skilled practice by using particular materials, tools, machines, or media with the sole purpose of making increasingly well-executed artifacts (McCullough, 1996, p. 22). Taking this one step further, Sennett (2008) defines craftsmanship in an even broader sense by including artistic creation, designer activity, scientific research, and even software development. To him, craftsmanship refers to the enduring, basic human impulse to do a job well for its own sake (Sennett, 2008, p. 9). Not only do all crafts involve hand work and expertise, but they also involve an investigation into the capacities of their medium, a practice-driven passion, and moral value that transcends the final product. Hence, craftsmanship is not only about the final product but about the process itself.

3. A FRAMEWORK FOR THE PROCESS OF CRAFT

How exactly does a craftsperson develop their skills and obtain some sort of expert craft knowledge? How does a craft object become better in quality? The answer to these lies within the deep and ambiguous corridors of design cognition. The multifaceted process of craft encompasses how crafters think about, solve, and approach design problems, which also implicates practical experience. Here, the process of craft will be interpreted by associating the ideas of Richard Sennett with design cognition perspectives. According to Sennett (2008), there are three aspects that build up the quality of a creative craft practice: the rhythm of knowledge production, the relationship between

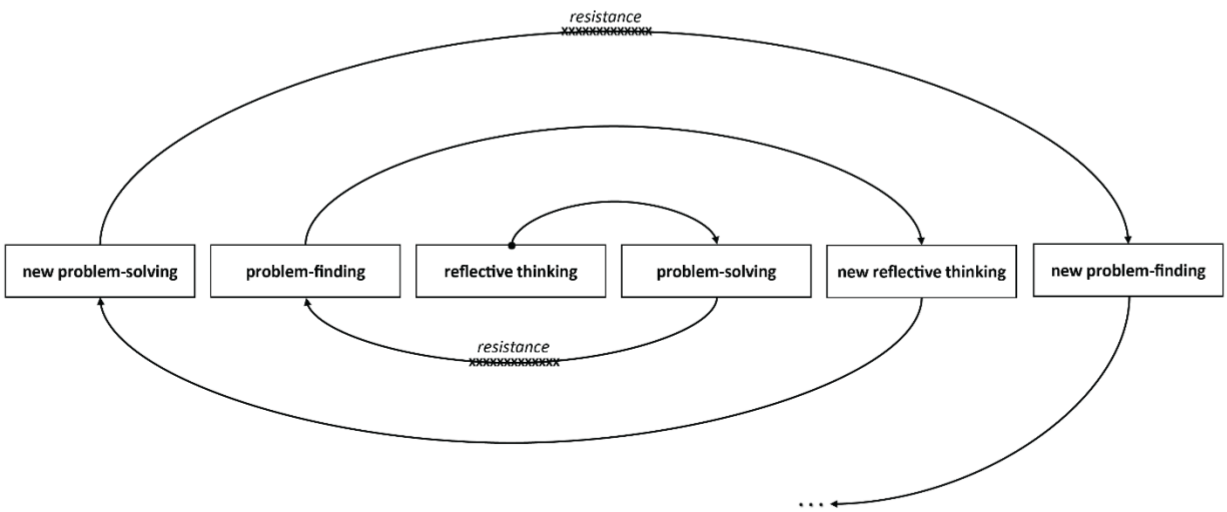

Figure 1: The craft process and skill development (developed by the author).

problem-solving and problem-finding, and the time of craftsmanship which is a slow time (Figure 1).

3.1 Rhythm of Knowledge Production

Think of a young ceramic artisan, let's call her Lola, learning the basic technique of throwing clay on a pottery wheel to create simple cylindrical forms. In the beginning, she consciously pays attention to every little movement from the pressure applied by her hands, and the speed of the wheel to the positioning of her body. She practices centering the clay while pulling it upwards and shaping it evenly. At this stage, Lola is extremely focused on each step, carefully following instructions, explicitly thinking, and making adjustments as she encounters difficulties. All these movements and actions she performs deliberately and with intense concentration are explicit knowledge. After repeated practice, centering the clay becomes second nature to Lola. She becomes adept at creating cylindrical forms without needing to think through each step explicitly. Her movements become more fluid and natural. What was explicit before, becomes tacit knowledge. Polanyi explains that such tacit knowledge "can be established only after it has been interiorized and extensively used to interpret experience" (1966, p. 21).

Lola may have mastered crafting cylindrical forms; however, she encounters a new challenge when she attempts to create bowls. Lola discovers that the techniques for throwing cylinders do not directly translate to bowls. For instance, the way she pulls the clay up to form tall, straight walls for cylinders does not work when she needs to create wider, curved shapes for bowls. She faces a dramatic resistance, as her bowls collapse or come out unevenly. At that point, there is a kind of explicit knowledge unpacking through the activity. What was formerly tacit becomes dredged into explicit consciousness because something does not work right.

3.2 Problem-Solving and Problem-Finding

Now, this is a problem Lola has to solve. Recognizing the problem, she revisits her technique. The initial tacit knowledge must be unpacked and re-evaluated. She reflects on her current knowledge repertoire and past experiences to try new design moves, make new decisions, and take new actions. This here, is a reflective thinking[2] process that involves building design knowledge through exploration and experimentation. Lola experiments with the clay, applies pressure differently, uses her hands to widen the base, and gently curves the walls outward. As she engages in various interactions, different internal representations of the material get composed in her mind. Through experimentation, Lola discovers new ways to position her hands and apply pressure, transforming her skill into a more nuanced and varied practice. Over time, these new techniques also become tacit for her. She can now switch between different methods fluidly, without conscious thought. Yet again, once she solves this problem, new ones arise. In fact, each solution Lola discovers opens up a new set of challenges. For example, her mastering the technique of applying a consistent glaze leads her to explore how different glazes interact, prompting questions about the chemical properties of the materials she uses. This never-ending cycle of problem-solving leading to problem-finding, followed by problem-finding leading to reflective thinking, and so on, ensures the refinement of Lola's craftsmanship. Hence, the crafting process and skill development appear as a growing spiral. By taking inspiration from Gürer et al.'s (2015, p. 167) hermeneutical spiral visualization, **Figure 1** depicts the relationship between reflective thinking, problem-solving, and problem-finding. There are two remarkable implications of this cycle. First, there is no complete and finished craftsmanship because there is no one right way to do something. When we develop a skill, we learn many different ways to perform the same kind of activity. Second, craft only thrives when there is a resistance, a change because they lead to problems leading to reflective thinking leading to problem-solving.

3.3 Slow Time

Lola's journey in pottery is marked by the slow, deliberate practice that Sennett (2008) emphasizes. When learning to throw a pot, Lola works slowly, often spending hours just centering the clay and shaping a simple form. This slow practice allows her to deeply understand the material's behavior and how subtle changes in her technique affect the outcome. Hence, the time of craftsmanship is a slow time. When you slow down a practice, the consciousness of the activities comes to the fore in a sequence. To do something incredibly slowly stimulates a mini

[2] For more information on reflective thinking, see Schön (1987, pp. 44-79).

version of tacit-explicit-tacit rhythm as the craftsperson dwells in the things they do. However, this dwelling is different from what Heidegger talks about. To Heidegger (1971), dwelling is a form of immersion in which ultimately there is a release. When you dwell in something slowly, you gradually become absorbed, and there is a kind of catharsis, so you are at peace. Meanwhile, for Bergson (1910), when things are slow, you are less at peace. The slower the time gets, the less confident you get about what you are doing. Bergson (1910, pp. 100-122), describes such immediate knowledge of consciousness as being temporal, or in his terms *la durée* (the duration). In *la durée*, there is no juxtaposition of events over time; hence, no mechanical causality. It is the lived time that is filled with subjective lived experiences. Therefore, the slow time of the craftsmanship is more of a Bergsonian time. When Lola practices pottery, she inhabits the time of *la durée* rather than the time of surrender to being.

4. CRAFTSMANSHIP IN COMPUTATIONAL DESIGN PRACTICES

Computational design acts as an umbrella term referring to design practices that employ computing techniques and computational thinking such as algorithmic, parametric, and generative design (Caetano et al., 2020). Computational design practices leverage a variety of digital tools to facilitate the design process or optimize performance, such as Computer-Aided Design (CAD) tools, parametric design tools, graphic programming tools, scripting and programming languages, Building Information Modeling (BIM) software, various simulation, visualization, and analysis tools. The framework of the craft process can be observed in computational design practices, where craftsmanship intersects with digital tools and algorithms. Sennett (2008) argues how problematic it is to put digital and craft in opposition because such opposition assumes that the digital era leaves the traditions and modalities of performing a craft behind. On the contrary, digital simply introduces another form of craftsmanship. Devendorf et al. (2020) point out how researchers tend to inadvertently romanticize craft, presenting it as a primitive or poetic counterpart to modern computational methods, and how such a dichotomy overlooks the inherent technical expertise within craft practices themselves. In reality, both traditional crafts and computational design involve complex problem-solving, skill development, and technical proficiency (Cheatle & Jackson, 2023). Therefore, rather than seeing computational design as a departure from traditional craft, it can be seen as a continuation and evolution of craftsmanship, where digital tools and algorithms are integrated into the craft's long-standing iteration, creativity, and expertise processes. Digital or not, any skillful practice can be considered as a form of craftsmanship. It just depends on whether the practice is performed as a craft or not. Hence, there is the craft of the digital rather than the craft being inserted within a kind of digital envelope. This craft manifests itself in computational design through several key characteristics. To fully understand computational design as a craft, it is essential to examine its key characteristics, such as open systems, nonlinearity, complexity, ambiguity, thinking outside the discipline, and tool-making. These characteristics are fundamental to demonstrating how computational design practices can extend beyond mere technical processes and incorporate a dynamic interplay of skills, creativity, and adaptability.

4.1 Open Systems and Nonlinearity

The computational design practice that arouses problem-solving, reflective thinking, and problem-finding, consists of a nonlinear open system. In systems theory, open systems imply systems that engage in exchanges of energy, matter, or information with their environments through input and output flows (Von Bertalanffy, 1950). If a practice is structured to achieve a certain specific goal, the person in training will reach the goal and be done with the problem (Sennett, 2008, p. 38). In contrast, an open system does not have a fixed end. It connects problem-solving to problematizing rather than closing a problem down and encourages exploration. Now, why nonlinear? In mathematics, linear equations or linear systems can be broken into pieces. Each piece can be analyzed separately and solved, and finally, all the separate answers can be combined. The whole is exactly equal to the sum of its parts. Whereas the parts in a nonlinear open system cannot be broken down this way. There is a non-proportional relationship between the input and output changes. Thus, the whole system has to be examined at once as a coherent entity. For example, Flemming Tvede Hansen's 3D clay printing practice embodies a nonlinear open system in computational craft (Hansen, 2021; Hansen et al., 2019). By integrating robotics with traditional ceramics, he extends the craftsperson's capabilities, fostering continuous exploration and allowing for intricate detailing and repetitive patterns beyond manual limits. Similar to evolving from explicit to tacit knowledge through gradual practice, Hansen's work evolves through iterative experimentation and reflection. The process is not linear but involves constant experimentation, leading to new questions and challenges rather than merely solving predefined problems. The integration of new technologies with traditional methods exemplifies the dynamic nature of open systems and highlights the importance of flexibility and responsiveness in creative practices. Celani and Vaz (2012) also emphasize how open systems and non-linear design processes enable designers to create flexible models that can respond to a variety of inputs and constraints in real time. This flexibility is crucial in creative practices as it enables designers to maintain a balance between artistry and technique, ultimately leading to more refined and meaningful creations.

4.2 Complexity and Ambiguity

A complex system is "a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution" (Mitchell, 2009, p. 13). This means that complexity emerges in the course of evolution through the feedback and sifting of information, rather than existing in a preordained and programmed outset. For instance, in computational design, generative approaches employ systems with unpredictable behavior, where simple rules lead to complexity. These include Shape Grammars, Lindenmayer Systems, Cellular Automata, Agent-Based Systems, and Genetic Algorithms (Singh & Gu, 2012). Generative approaches can be utilized in design in a functional and exploratory way. The functional way focuses on specific problems, seeks answers, improves the design and related efficiencies, and closes the topic. The exploratory way connects problem-solving to problem-finding and encourages reflective thinking. In an exploratory generative design, the designer may play with parameters and rules, reflect on changes, form analogies, interpret and reformulate behaviors, explore randomity, and look for emergence (Topaloglu, 2023). Here, generative systems act as open complex systems, where parts of the system interact within a larger context. Sometimes, the system exhibits properties or behaviors that are absent in its individual components – known as the emergence (O'Connor, 2021). Along with the complexity, the randomity of both emergent properties and the whole system leads to ambiguity. Oxman (2006) claims that such ambiguity in exploratory computational design serves as a source of creative potential. The ambiguity directly corresponds to the resistance in the craft process. To deal with unexpected outcomes and anomalies, the designer is forced to have a rhythmic journey between explicit and tacit knowledge. In this regard, 3D clay printing often embodies ambiguities because it involves taking actions with no clear outcomes (see Shi et al., 2019; Van Der Veen et al., 2019). We also see this in Michael Batty's computational design study in the field of urban planning and design. Batty creates complex urban growth models of cities through Cellular Automata, Agent-Based Systems, and Lindenmayer Systems (see Batty, 2007a, 2007b). As the simulation runs and urban patterns emerge, Batty's understanding emerges from the system's behavior rather than explicit programming. He encounters resistance and explicit knowledge unpacking when unexpected urban patterns or challenges (e.g., traffic congestion, resource allocation) emerge that require revisiting. He experiments with the model’s parameters, navigates through ambiguities, and reflects on emerging properties. Engaging with complex datasets, varying parameters, and unpredictable outcomes enriches his computational craft process and fosters deeper understanding.

4.3 Thinking Outside the Discipline, and Tool-Making

Computational design encourages interdisciplinarity by combining knowledge and techniques from diverse fields like art, architecture, engineering, and computer science. This interdisciplinary nature forces practitioners to think outside the traditional boundaries of their discipline and embrace new insights. For instance, Hansen (2021) and Batty (2007a) both ventured beyond their comfort zones and experimented with new methodologies. Without the impetus for growth and challenge, practitioners risk stagnation in their craft, limiting their skills and knowledge. In contrast, thinking outside the discipline invites open-ended inquiries and continuous exploration. Such a mindset leads to countless opportunities for problem-finding and the dynamic interplay between tacit and explicit knowledge, resulting in the continuous refinement and evolution of one's craft. Furthermore, tools that are used in computational design practices are generally not served on silver plates. There are countless examples regarding the tool-making aspect of computational design. For instance, Devendorf et al. (2023) created a parametric design tool for complex weaving patterns. Tamke et al. (2017) developed simulations utilizing various algorithms and artificial neural networks to be able to design and build their *Lace Wall*. Most of the time, computational designers need to become proficient in some coding languages like C#, JavaScript, and Python, or visual programming software like Grasshopper for Rhino. This necessity highlights the significant challenge posed by the absence of readily available design tools tailored to their specific needs. Computational designers often find themselves in a landscape lacking comprehensive tools that align with their design problems and processes (Nisztuk & Myszkowski, 2018). This landscape compels designers to develop their own tools and scripts, a task that requires not only technical proficiency but also creativity and resourcefulness. In this context, the lack of a concrete design tool awaiting the designer to use echoes Heidegger's notion of the broken hammer. Heidegger (1927/2007) points out that the moment a hammer breaks, it loses its utility and simply exists as an object, separate from useful tools until it is repaired or replaced. It is when we encounter the broken hammer that we consider the network of purposes that it is a part of. The ordinary immersion into the craft process does not make room for such reflection. Only when something – a resistance, a change, or a challenge – disrupts this absorption into practice, does the crafter get to have the necessary distance to contemplate their practice. Just as a broken hammer prompts reflection not only on its raw materials but also on its role within our network of purposes, so too does the absence and the creation of digital tools in computational design invite us to contemplate the essence of our creative processes. The act of tool-making requires a deliberate pause in ordinary absorption into tasks, in which designers can gain critical distance and reflect on the broader implications of their design decisions. Moreover, the process of coding itself becomes an exercise in problem-finding and solving (as we also see in Sennett, 2008), where designers navigate complexities and uncertainties outside of their discipline to craft custom algorithms and parametric models.

5. WHAT ABOUT THE LACK OF CRAFT?

Now, let's sit on the opposite side of the table. While computational design practices can embody many principles of craftsmanship, there are instances where we cannot consider it a true craft. Craftsmanship is inherently exploratory and involves a profound engagement with the material or medium, continual problem-finding, and iterative problem-solving. However, certain computational design practices fall short of these criteria. If a computational design practice is overly rigid, aiming solely for efficiency and optimization without room for exploration and experimentation, then it should not be considered as a craft. For instance, when a designer relies heavily on predefined algorithms and templates to generate designs without questioning or modifying them, the process becomes mechanical. Again, if the focus is merely on solving predefined problems without seeking new challenges or questioning existing parameters, the practice becomes static. Or when designers use automated tools just to shortcut generate designs with minimal input or understanding, it fails to become craftsmanship. These kinds of approaches lack the open-ended inquiry and reflective practice that are central to craftsmanship.

In this regard, resistance in traditional craftsmanship plays a crucial role in fostering a deep engagement with the material and shaping the crafter’s skills and design approach. Although it is often neglected in computational design practices, the idea of resistance is essential to understanding the potential and limitations of computational methods and digital tools. Resistance in this context does not solely refer to physical material constraints but also to the inherent challenges posed by the algorithms, tools, and processes used. For instance, as it was mentioned before, ambiguity can serve as a form of resistance. However, computational practices have a tendency to streamline design processes to ironically eliminate the resistance and create a more efficient but less engaging design environment. When computational design tools and algorithms are too accommodating, they remove the need for iterative exploration and experimentation. Such an absence of resistance can lead to a superficial design process in which the designer merely follows predetermined paths without any skill development. Therefore, computational craftsmanship requires design environments that challenge and stimulate reflective thinking, capable of introducing conceptual and procedural obstacles to force designers to think critically and creatively.

Another issue that dries out the potential craftsmanship in diverse studies conducted at the dissertation level by computational design researchers is the development of linear workflows. Such workflows present a simple formula that will lead to a certain design "solution" if you do this from point A to point B. It leaves no space for exploration and kills the potential of craft in the practice right away. Furthermore, the over-reliance on computational efficiency can strip away the unexpected discoveries that are important in craft-based practices. By prioritizing speed and accuracy over the creative process, designers may miss out on unique outcomes that emerge from a more hands-on, inquisitive approach. If computational design is to be elevated to the level of true craftsmanship, it must embrace a philosophy that values process as much as product, allowing for unexpected insights and growth. If we want to nurture craft in computational design practice, then our workflows must invite complexities and ambiguities themselves, and be nonlinear.

6. CONCLUSION

In conclusion, computational design practices possess great potential with the transformative capabilities of digital tools and methodologies for today's craftsmanship. Deeply rooted in human history and culture, craftsmanship has significantly evolved from its origins in ancient civilizations to its current state in the digital era. Today, computational design further expands the horizons of craftsmanship via tools and techniques like 3D printing, parametric design, and generative algorithms, enabling craftspeople to explore new creative avenues and problem-solving methods. The study explored how the rhythm of knowledge production and problem-solving in slow, deliberate practice characterizes traditional craftsmanship. In computational design practice, these principles manifest in open and nonlinear systems that encourage exploration and experimentation. Complexity and ambiguity are embraced as opportunities for growth rather than rigid obstacles, mirroring the iterative and reflective nature of traditional craftsmanship. Moreover, the act of tool-making in computational design underscores a critical aspect of craftsmanship: the deliberate and thoughtful engagement with technology. Just as craftspeople select and hone their tools, computational practitioners craft algorithms and parametric models, reflecting on their design decisions and the broader implications of their work. However, it is essential to acknowledge the potential pitfalls in computational design that may undermine craftsmanship. Processes that prioritize efficiency or functionality over exploration risk eliminating craftsmanship and turning it into a mechanical practice devoid of creativity and the human touch. To preserve and nurture craftsmanship in computational design, it is imperative to foster complexity, ambiguity, continuous exploration, and reflective thinking. Integrating these elements ensures that the essence of craftsmanship endures, even as technology evolves, maintaining a balance between tradition and contemporary. By recognizing and appreciating the human element within digital practices, we can pave the way for a future where craftsmanship continues to thrive in new and unexpected forms.

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