INTERNATIONAL DESIGN CONFERENCE - DESIGN 2018
https://doi.org/10.21278/idc.2018.0242

A REVIEW OF MAKING IN THE CONTEXT OF DIGITAL FABRICATION TOOLS

L. Corsini and J. Moultrie

Abstract
The review considers the role of making in the context of digital fabrication tools. Digital fabrication is having significant impacts on design and is challenging traditional production paradigms. The study reviews literature on making to conceptualise the activity of design-in-making, where making becomes an integral part of the design process. The paper analyses an improvisational model of design to suggest practical ways to achieve improvisational making when using digital fabrication, with the goal of achieving creative design.

Keywords: digital design, digital manufacturing, design creativity, design process, design theory

1. Introduction
"*A new digital revolution is coming, this time in fabrication.*" Gershenfeld (2007)
In the decade since Gershenfeld declared a digital revolution, the growth of new digital fabrication tools (e.g. 3D printing, CNC milling, laser cutting and robotics) has changed the way in which products are designed and manufactured. Historically, design and making have been considered as two discrete and linear stages in the design process, however, the advent of digital fabrication is radically challenging this dominant paradigm. The renewed interest in making among designers and users is also noted in the growing popularity of personal fabrication technologies, which can be found in emerging informal design environments such as fab labs or make spaces (Ratto and Ree, 2012).
The relationship between creativity and technology has been widely discussed, yet it remains unclear how the use of digital tools is influencing creative design. On one hand, digital tools may enable designs that were not previously possible, therefore expanding creativity (Ford and Despeisse, 2016). On the other hand, digital tools may restrict design (Heidegger, 1977; Philpott, 2012), encourage the production of replicas (El-Zanfaly, 2015) and reduce the potential for improvisation (Willis, 2011; Pinochet, 2016). The following paper argues that by integrating the stages of design and making, creative results might be achieved through the use of digital fabrication tools.
In this review, a history of design and making are considered in order to reveal new possibilities for the design process in the context of digital fabrication. In particular, the review considers how engagement with making might offer potential for creativity when using digital fabrication tools.
The paper is structured as follows. First, a comparison of *morphogenic* and *hylomorphic* models of design. Second, a discussion of creativity and digital fabrication. Third, an exploration of improvisation, uncertainty and emergence in relation to creativity and digital fabrication. Next, a consideration of new roles for the designer including the designer-maker and designer-tool-maker. Finally, the paper analyses an improvisational model for creative design, drawing practical suggestions for the use of digital fabrication. The paper concludes the implications of the findings for design research, providing proposed areas of research for further study.

2. Design and making: A morphogenic approach

The separation of design and making that is typical of the modern design process, is grounded in the *hylomorphic* model that emerged from the philosophy of Aristotle. In this tradition, matter is regarded as a passive body onto which action is imposed. Specifically, there is a clear definition of the antecedent design phase which is finished prior to the subsequent making phase.

"*Of comings into being and movements, one part is called understanding and the other producing - what proceeds from the starting point and form is understanding, what proceeds from the final stage of understanding is producing*." (Aristotle, 1971, p. 1032b14-17)

This theoretical perspective has underpinned the separation between mental cognition and physical production. In contrast, salient criticisms of the hylomorphic model have emerged from Simondon (2006), Deleuze and Guattari (1980) and more recently, Ingold (2013). Ingold reflects on the history of architecture to consider the evolution of the design process, with respects to design and making. He notes the influence of Renaissance architect, Leon Battista Alberti, who clearly makes the distinction between mental planning and physical construction in his work *De Re Aedificatoria*. Similarly, Le Corbusier (1947) echoes this view of design as an a priori activity, in which drawings and models are used to complete the design before the construction process.

"*Man walks in a straight line because he has a goal and knows where he is going; he has made up his mind to reach some particular place and he goes straight to it"*. (Le Corbusier, 1947, p. 11).

This separation of design and production has since become the de-facto way in which we describe and characterise design. Indeed, the Oxford English Dictionary definition of design is: *"A plan or scheme conceived in the mind and intended for subsequent execution" or as a verb "To make drawings for the construction or creation of (something, as a building, object, garment, etc.) according to certain aesthetic criteria; (b) to make plans for the production of (a device, product, etc.) according to structural or functional criteria (sometimes without the implication of aesthetic requirements); (c) (in extended use) to conceive, devise, plan (something immaterial, as a scheme, system, programme, etc.)"* (OED, 2017).

However, Ingold (2013) argues that this was not always the case. In the medieval times, the use of drawings was primarily descriptive as oppose to prescriptive. Referencing Hugh of St Victor (1961), Ingold points towards the conception of medieval masonry as an iterative and evolving design process.

"Great medieval buildings were not assembled like puzzles from pre-cut pieces, nor were they finished when the last piece was slotted into place. A better analogy…might be the patchwork quilt." (Ingold, 2013, p. 54).

Simply put by Dewey: "*Plans grew as buildings grew*" (Dewey, 1934, p. 59). Rather, the current model of design as a planned and a priori activity can be viewed as a result of the paradigm shift during the Renaissance period, that was furthered by the growth of mass production during the Industrial Revolution. The demand for high volume, standardised products necessitated a highly controlled manufacturing process, and therefore, required detailed designs to be planned in advance. The separation of design and making was further compounded by the growth of an academic engineering education during 20th Century that focused on new "scientific methods" (Stolterman, 1994). These pedagogies considered design from a theoretical perspective, and undermined the value of hands-on experience.

However, with the rise of the so called Third Industrial Revolution (Rifkin, 2011), the growth of digital fabrication tools is challenging perspectives that separate the stages of design and making. Notably digital fabrication facilitates alternatives approaches to mass production, namely mass customisation and the personal manufacturing of one offs (Mellis, 2015). Consequently, the traditional hylomorphic model that underlies mass production, is no longer paramount. Instead of relying on a highly controlled manufacturing process, design can leverage the potential for spontaneity in making, where variability is considered to be an advantage. Building on this context, Ingold advocates a *morphogenic* approach that positions materials and people in the context of a situated environment. Adopting the framework of this morphogenic model, it can be viewed that making is an irreducible element in the design process and that design can in fact occur in-vivo during making. This is consistent with Schon's theory of reflection-in-action that depicts the designer in a reflective conversation "*among the maker, the material, the tools and the object in-the-making*" (Schon, 1992).

Likewise, Archer (1991) argues that expression through construction is fundamental to design reasoning. This dialogue between design and making can be found in the work of Antoni Gaudi, who relied heavily on prototyping and used hanging chains to define catenary curves. By inverting these curves, Gaudi was able to define exact angles and dimensions for La Sagrada Familia (Burry, 2005).

Taken together, these perspectives provide evidence that opportunities for design exist in the process of making. Expanding on this idea, the phenomena can be conceptualised as *design-in-making.*

3. Digital fabrication and creativity

Historically, it has been suggested that digital tools impose high levels of control, whereas non-digital tools facilitate exploratory design and allow for elements of surprise. Heidegger (1982) highlights the inherently limiting capacity of technology. He describes how:

"*The typewriter tears writing from the essential realm of the hand…Mechanical writing deprives the hand of its rank in the realm of the written word and degrades the word to a means of communication…The typewriter makes everyone look the same*." (Heidegger, 1982, p. 80-81).

Similarly, David Pye (1968), although to a somewhat lesser extent, confirms this view, identifying the trade-off between quality and creativity as a result of technology:

"*Typewriting represents an intermediate form of workmanship, that of limited risk. You can spike the page innumerable ways, but the N's will never look like U's, and however ugly the typing, it will almost necessarily be legible."* (Pye, 1968, p. 21).

In contrast, Pye presents handwriting with the pen as an example of the 'workmanship of risk', and modern printing as an example of the 'workmanship of certainty'. It would be incorrect, however, to use Pye's analogy to classify digital tools as the 'workmanship of certainty' or non-digital tools as the 'workmanship of risk'. Just as Pye admits the demarcation between hand work and machine work is meaningless - can writing with a pen truly be hand work? - a superficial demarcation between digital and non-digital tools with respects to uncertainty is incorrect. Notably, McCullough (1998) observes the relationship between digital work and craft practice, identifying analogous processes in traditional and digital practice. On these grounds, it is possible that digital tools might be used in an exploratory and improvisational way.

These views are in contrast to traditional design paradigms which conceive that technology is a means to implement control, quality and precision in the design process. The Design Methods Movement in the 1960s, highly influenced by developments in operational research, artificial intelligence and computer technology, aimed to create a scientific method of design by reducing the process into its constituent parts and replacing repetitive work with technology (Celani, 2012; Langrish, 2016). This movement influenced the predominant views of the design process as a means of devising courses of action to change situations (Simon, 2008).

Against the view that design is highly planned and purposeful, new applications of digital fabrication challenge the theoretical model of control. Oxman (2006) points out the growth of non-deterministic design processes, which can be observed in the practice of designers who use generative and parameter-based design. This is consistent with findings in Kolarevic (2004) who notes the discovery of emerging forms in parametric design, and in Carpo (2011) who places emphasis on digital 'form finding' as oppose to prescriptive design solutions. Indeed, it is found that design does not develop along a single pre-determined trajectory, progressing inexorably from idea to manufacture, but must respond to situated factors, resulting in a range of possible ideas (Holzer, 2008; Harrison et al., 2015). Sass and Oxman (2006) observe that that generative design and rapid prototyping can be integrated into one process.

Similarly, the trend towards to non-deterministic, emergent design processes is noted in the research of new production processes. At ETH Zurich, Dörfler et al. (2016) showcase a large-scale additive manufacturing technique, using small scale robotics to remotely project loam blocks. Rather than building a replication of a pre-determined design, design parameters are set and sensors monitor the structure during construction, providing feedback to the robots, such that its settings can be adjusted. In many ways, this construction approach is reminiscent of Ingold's (2013) conception of Medieval masonry, which was discussed earlier. Consequently, there is precedent for the ways in which design might exploit the speed and power of digital technologies to revive the benefits of a pre-industrial era. Emergent designs, which were previously developed through iterative methods of trial and error, might now be manufactured in a way that is both efficient and achieves robust and optimised design.

Furthering a critical analysis of traditional design paradigms, Preston (2012) reviews the work of Aristotle, Marx and Dipert to elucidate the 'centralised control' model which dominates material culture. The 'centralised control' model assumes that:

1. a mental design phase occurs prior to construction;
2. mental design is formed by an individual;

3. the design is fully prescriptive;
4. the construction phase is the unintelligent execution of the design.

Preston posits that this model inherently encourages replication as opposed to the generation of novel ideas. Furthermore, she argues that planning theories of action are deeply flawed, in so far as they neglect the improvisatory and distributed nature of creativity, which is collaborative and spans both mental and physical activity. Notably, Suchman's (2006) definition of situated actions reframes actions as flexible and contextual, limiting the value of pre-planned actions. Significantly, these positions both challenge the view that associates digital fabrication with control and planning, and also introduces new ways of thinking about making as a process where uncertainty is crucial.

4. Improvisation, spontaneity and emergence

The concept of improvisation is widely discussed with respects to emergence in literature. Several definitions of emergence exist in the fields of computation, thermodynamics and function (Cariani, 1991; Jankovic, 2012; Chen and Crilly, 2016). Emergence can be described in the context of the design process: "*emergence is the process of making features explicit that were previously only implicit*" (Gero, 1996). Gero proposes that emergence can operate in an additive or substitutive sense, expanding the design space or replacing areas of the original design space, in the search for new design schemas. Ultimately, this search for new schemas facilitates the development of creative design. In later work which explores the relationship between emergence and creativity, it is proposed that novelty is an indicator of emergence, in the sense that novelty expands design possibilities, generating results that could not have been predicted (Saunders and Gero, 2000). The explication of the relationship between emergence and novelty is consistent with the pragmatist theories of George Mead:

"*The present in which the emergent appears accepts that which is novel as an essential part of the universe, and from that stand point rewrites its past. The emergent then ceases to be an emergent and follows from the past which replaces the former past.*" (Mead, 1932, p. 11).

Mead emphasises contingency, proposing that emergence can only be understood after its occurrence. In the same way, Mead argues that even the scientist, who is perceived to work in a deterministic manner, looks forward to an emerging interpretation and retrospectively interprets the data. This description of emergence is consistent with the concept of the 'creative leap' which is noted by Dorst and Cross (2001) in an examination of creativity, otherwise referred to as abductive reasoning.

Accordingly, emergence can be viewed as a dynamic, improvisational, contingent and situated process. Returning to Mead's exposition of emergence, it can be understood that the physical experience is fundamental. In a description of a young boy exploring the world, Mead posits that the child understands his own being through the physical experience of his environment acting upon him.

"*His surroundings stretch away on all sides… Meantime the pressure of his body and the grasping of his hands have to localise things from an inside attitude and he finally reaches himself as a thing through the action of other things upon him*." (Mead, 1932, p. 122)

Consequently, agency is asserted to non-human actors, in so far as the environment is responsive and shapes an understanding of the world. Further expanding upon the concept, Newton's laws of motion (that each action has an equal and opposite action) are considered, to elucidate the symbiotic relationship between the subject and object. This is consistent with the work of Latour (1987) and Law (1991) with regards to Actor Network Theory, which posits that all actors in a system have agency. It follows that, any system of multiple actors must be dynamic. Mead draws inspiration from the biological world, where this is especially evident, arguing that all systems are dynamic and that new states are therefore constantly emerging. In this account, action is identified as a fundamental part of understanding, where cognition is no longer a purely mental activity, but is also localised in physical activity. Similarly, Dewey (1934) makes clear that without physical embodiment, an experience is incomplete, concluding that perception must involve all the senses and emotions. Taken together these perspectives underscore the role of the physical in the emergence of design, therefore revealing the importance of making in the design process.

The account of emergence challenges the reductionist epistemic of design that advocates the designer as the central planner. In particular, the self-organising, bottom-up nature of emergence, is identified in a number of studies (Van Alstyne and Logan, 2007; Sato and Matsuoka, 2009; Jankovic, 2012). Whereas in a traditional top-down approach, the designer starts with a desired outcome and derives an optimum solution in a reductionist manner, a bottom-up approach is iterative and self-organising, as it adapts to a changing design environment rather than focusing on a single overarching intention. Experimental findings from Knight and Stiny (2001) and Cannaerts (2009) conclude that digital and computational design can generate emergent results. Consequently, the designer is not a controller, but an influencer of the design process.

So then, the following question evolves: how can designers recognise viable opportunities and practically use (or influence) emergence in the design process? Schon (1983) notes the significance of the 'surprise' in creative design. Marenko (2015) introduces the concept of the 'glitch' as a method for expanding design potential, where the accident or error is reframed as a productive opportunity. In this sense, ambiguity is viewed as the corollary of improvisation and emergence (Knight and Stiny, 2001). It is also suggested that a new method of 'digital craft' may supersede traditional design methods, which poses a challenge for designers. How might designers adapt their skills to explore ambiguity in the design process? Research has shown that tolerance to ambiguity is related to creativity, and that some personality traits may be better suited to managing ambiguity (Tegano, 1990). In fact, failure - and tolerance to failure - may also be an important component in creativity (Vossoughi and Bevan, 2014). Moreover, Dewey (1934) identifies that making use of emergence requires experience, providing the analogy of a volcanic eruption which results for a long period of compression:

"*Spontaneity is the result of long periods of activity, or else it is so empty as to not be an act of expression*". (Dewey, 1934, p. 72)

Consequently, it can be concluded that while an emergent method is not planned, it requires the active engagement and intentionality of the reflective designer, who is continually interacting with the design, the environment, the object. Clearly, active engagement with design and making provides a basis for exploring an emergent process, and resultantly is a driver for creativity in design.

5. The designer-maker

As the boundaries between design and making become more blurred, there is a need to consider the emergence of informal design environments, where designer-maker identities overlap. In particular, the increased availability of personal fabrication tools has generated a new cultural phenomenon - the Maker Movement. The Maker Movement is premised on the concept of a community of makers, who create physical and digital artefacts for their own use (Papavlasopoulou et al., 2016; Chu et al., 2017; Christensen and Iversen, 2017). Originally, Makers occupied fabrication spaces, such as fab labs or make spaces, however an increasing interest in Maker culture has resulted in the expansion of design spaces to a range of contexts, such as schools, museums and universities (Christensen and Iversen, 2017). This dualist role of *designer-maker* reflects the shift in design process, where making is no longer a reducible component of design, to be performed once the design is fully resolved.

5.1. Tool making

Another phenomenon associated with the growth of digital fabrication tools is the emerging proposition of the designer as a *tool-maker*. In this case, designers are no longer simply users of manufacturing tools but they are actively involved in adjusting fabrication tools or developing their own fabrication tools. In ceramic design, there are a number of designers, including Jonathan Keep, Oliver Van Herpt and Claire Wernier, who have created their own 3D printing tools to print clay. In product design, designers such as Joris Laarman and Dirk Vander Kooj have created their own free-form additive manufacturing tools. Drummond Masterton, a conceptual product designer reflects on how understanding the fabrication tools he uses is an integral part of his work:

"*testing numerous machine settings, adjusting large segments of machine code and changing or making tools for the machine to use"* (Bunnell, 2004).

The concept of the role of 'designer as a tool builder' is identified by Aish (2003), and Oxman (2006) concludes that there is a new role for the designer as a "*toolmaker of customised design media*". It follows that making does not just refer to production of artefacts but it some cases, involves the production of new tools.

6. An emergent design process using digital fabrication

Earlier the following question was identified: how can designers recognise viable opportunities and practically use (or influence) emergence in the design process? In order to explore this question, Preston's

(2012) alternative proposition to the 'centralised control' model is considered. Preston introduces the improvisational agent as the designer(s) that coordinate their work by using alternative resources to plans. Focusing on descriptive (rather than prescriptive) strategies, such as habits and practices, there is an emphasis on non-explicit patterns of activity for governing the design process. Specifically, three main strategies are identified, which Preston proposes can be used by solitary or collaborative agents:

1. appropriate and extend;
2. proliferate and select; and,
3. turn-taking.

Each of these strategies will be examined in turn, in an attempt to understand how the various approaches might facilitate improvisational, emergent practice in a design process, when using digital fabrication. Finally, it is considered that in some cases the digital fabrication tool itself naturally creates variability. Preston's model is therefore expanded to include a fourth strategy in response to this:

4. exploiting spontaneity

6.1. Appropriate and extend

Preston gives the example of how Nathan Sheppard, who upon being stuck writing lyrics for 'Lying in Grass', was provided with the first two lines of the song by his co-performer Will Greene. This provided him with a starting point and he went on to immediately complete the song lyrics. In other words, the strategy identifies how the improvisational agent can build upon the inspirations of pre-existing structures to appropriate or extend ideas - developing an idea further but also making revisions to the pre-existing structure through new interpretations and revisions. In the case of digital fabrication, designers might be provided with a partially created model or inspirations for designing a solution - a partial *ready-made*.
Blikstein (2013) describes how providing semi-structured instructions can assist students, however warns that examples should avoid being too prescriptive or trivial. In the design exercise, Blikstein describes the 'Keychain Syndrome' where students become fixated on a particular type of solution rather than exploring the full design space. He notes that they prefer to make simple, 'highly finished' results, as oppose to exploring non-trivial solutions. This study is consistent with extensive research on design fixation, which warns against the use of physical examples early in the design process, as they can constrain solutions (Vidal et al., 2004; Toh, 2014). Taken together, this argument leads to the hypothesis that that the provision of a partial ready-made solution can support improvisation in the design process. However, further investigation is needed to understand how to facilitate appropriation without initiating fixation.

6.2. Proliferate and select

The second strategy composes of two key activities, proliferate and select. Proliferate refers to, in Preston's words, the action of "*trying out several ways of proceeding before settling on one*". It is noted that the process of generating options can be time consuming and require a significant amount of effort. However, in some cases the use of proliferation can be implemented to significantly ease the process, by creating a bank of self-made, partial ready-mades, from which to later draw inspiration from. In the case of digital fabrication, the use of a design repository such as Thingyverse or GrabCAD might provide opportunities for designers to seek inspiration from.
Preston also suggests that introducing means of distraction into the environment may encourage increased likelihood of unintentional productions. Such unintentional productions she argues, serve as means to inspire creativity.
"They also sometimes use other items of material culture and/or aspects of the social environment as distraction devices, so that the doodling not only lacks a guiding intention, but also is not even the focus of conscious intention." (Preston, 2012)
It is possible that new, dynamic design environments, such as maker spaces, might provide opportunities for such creative 'unintentional productions'. Furthermore, the notion of unfaithful copying is introduced, whereby the designer begins by imitating another product and deviates from the original design, as a result of their own limitations or sensibility. In this way, unfaithful copying can result in the creation of something altogether new as opposed to appropriated. El-Zanafaly (2016) defines the model 'Imitation, Iteration and Improvisation' to encourage students to engage with making using digital fabrication. In this

process, the use of copying existing designs is presented as a valuable way of learning, allowing for analysis and interaction. In the iteration stage, the students are encouraged to modify a particular feature, for example the material or geometry. Finally, in improvisation, students are encouraged to create their own concepts. The model provides a good foundation, but offers a fairly constrained approach for imitation – students only copy one precedent – and provides limited guidance with respects to exactly how to iterate and to improvise. The model also relies heavily on the creative input of the students, and so, further work is needed to introduce more guidance and modes of inspiration, in order to support the creative process.

Taken together, these analyses suggest that firstly, the accessibility of self-made partial ready-mades might encourage inspiration; secondly, external inspirations (or distractions) might encourage improvisation; thirdly, that imitation might result in the creation of the new, not simply appropriated.

6.3. Turn-taking

Preston's third strategy for improvisation is turn-taking. Drawing upon references from baseball teams, jazz groups and Conversational Analysis, the nature of collaborative activity is highlighted as a key inspiration for improvisation. It is noted that high levels of organisation are achieved through the local organisation of agents, who behave according to local, normative practices. In a review of making, Resnick and Rosenbaum (2013) advise that that the maker needs to engage with people not just materials. Further reinforcing this position, Petrich et al. (2013) argue that solidarity (sharing tools, strategies and contributing to each other's work) is an important aspect of making. Youmans and Ohlsson (2005) argue that groups are better able to identify complex problems than individuals if group communication is good. This approach provides the basis for exploring new design approaches with respects to digital fabrication. Sharing design input or structured collaboration on designs in digital maker spaces might facilitate the emergence of creative design.

6.4. Exploiting spontaneity

Exploiting spontaneity is proposed as an additional strategy to complement Preston's model. Earlier the idea that digital fabrication is introducing new possibilities for creative design was discussed. Of note, the concept of the 'glitch' is reframed as a productive opportunity (Marenko, 2015). In the case of parametric design, the designer relinquishes the traditional control of the manufacturing process. Instead of starting with a pre-determined idea of the final design, the designer sets some parameters and the process of making allows for unforeseen designs to unfold. In addition to this method of *exploiting spontaneity*, other interfaces for interactive and spontaneous fabrication may also be possible. Notably, Willis et al. (2011) explore a method for direct interactive fabrication, presenting three prototype devices which use real-time inputs to directly affect fabricated outcomes: using inputs from a microphone to control wire bending to design jewellery; using potentiometers to sense the cutting path of a hot wire cutter; and, converting physical inputs into digital CAD representations. Similarly, Pinochet (2016) argues that by using interactive design and intelligent fabrication machines, it is possible to reconcile design and making through technology, and to reduce the creative gap. Consequently, these perspectives provide a basis for understanding different ways of exploiting spontaneity when using digital fabrication. Importantly, they signal a shift in thinking, away from the 'centralised control' model towards a model of *design-in-making,* where the production process itself demands improvisation.

7. Discussion

The main focus of this review has been to understand how making has changed as a result of the application of new digital fabrication tools. The paper started by exploring critical perspectives of the traditional hylomorphic model, drawing contrasting views to show that design and making are inextricably related. This perspective was conceptualised to identify the approach of design-in-making. Notably, this review undermines the 'centralised control' model of design, advocating a participatory and self-organising approach to the design process. This point of view is consistent with the emerging role of the designer-maker, which has been enabled by the advent of digital fabrication tools and development of new digital fabrication spaces.

Fab labs or make spaces are among some of the potential environments where designer-makers can explore new design-in-making approaches. There is a need to map out these informal environments and

to understand the extent to which these environments foster an improvisational design process and the ways in which this improvisational approach is having an impact on the design of artefacts. Specifically, further research is needed to understand how these informal environments for design and making might support more creative and effective design compared with the traditional design studio.
The review then proceeded to explore the relationship between digital fabrication and creativity. Expanding upon the concept of improvisation, uncertainty and emergence, the question of how digital fabrication might be connected to improvisational making was identified as relevant to the development of creative design. Finally, three improvisation strategies were considered with respects to digital fabrication and Preston's (2012) model was expanded upon to include *exploiting spontaneity* which considers how the production process itself creates opportunities for improvisation. The findings reported lead to the following hypotheses:

1. the use of a partial ready-made will support creativity when using digital fabrication tools;
2. imitation of existing products will support creativity when using digital fabrication tools;
3. collaborative making will support creativity when using digital fabrication tools; and,
4. the use of more interactive digital fabrication processes will facilitate creative outputs.

Some suggestions have been made for how each of these approaches might practically be used: leveraging collaborative design, designing using digital design repositories (such as Thingverse of GrabCAD); or using partially started solutions (referencing examples or features from alternative designs). However, further research is needed to explore these approaches in more detail. In particular, consideration needs to be given to potential creative conflicts that might result from adopting such approach. For example, studies relating to design fixation, offer alternative views on the role of ready-mades and should be investigated in relation to the suggested approaches.

8. Conclusion

The current paper has shown how the rise of digital fabrication has created a shift in thinking about design. An examination of the relationship between design and making over history has situated perspectives on how these two stages of the design process might be integrated. It can be understood that the separation of design and making has in many ways been related to technological progress since the Renaissance and Industrial Revolution. Of note, this review, contradicts the view that technology must impose high levels of control. In particular, the review identifies that digital fabrication offers alternatives to mass production, and resultantly provides a basis for exploring new ways of improvisational and creative engagement. Not only can the designer adopt strategies for improvisation when using digital fabrication tools, but the digital fabrication tools themselves can impose improvisational results. The paper has identified four improvisational strategies which support creativity when using digital fabrication. As a next step, there is a need to define methods for adopting these approaches as part of the design process. Such research would have significant implications for the field of creative design, as well as design education.

References

Aish, R. (2003), "Extensible computational design tools for exploratory architecture", In: Kolarevic, B. (Ed.), *Architecture in the Digital Age*, Taylor & Francis, London, UK, pp. 338-347. https://doi.org/10.4324/9780203634561

Aristotle (1971), *Aristotle's Metaphysics: Books Γ, Δ, and E*, translated with notes by Christopher Kirwan, Oxford University Press, Oxford, UK.

Blikstein, P. (2013), "Digital Fabrication and 'Making' in Education: The Democratization of Invention", In: Walter-Herrmann, J. and Büching, C. (Eds.), *FabLabs: Of Machines, Makers and Inventors*, Transcript Publishers, Bielefeld, pp. 203-221.

Bunnell, K. (2004), "Craft and digital technology", *World Crafts Council 40th Anniversary Conference, Metsovo, Greece*, World Crafts Council.

Burry, M. (2005), "Homer Faber", *Architectural Design,* Vol. 75 No. 4, pp. 30-37. https://doi.org/10.1002/ad.100

Cannaerts, C. (2009), "Models of / Models for Architecture: Physical and Digital Modelling in Early Design Stages", *Proceedings of 27th eCAADe Conference, Istanbul, Turkey, September 16–19, 2009,* eCAADe, Brussels, pp. 781-786.

Cariani, P. (1991), "Emergence and Artificial Life", In: Langton, C.G., Taylor, C., Farmer, J.D. and Rasmussen S. (Eds.), *Artificial life II: Studies in Sciences of Complexity*, Addison-Wesley, Reading, MA, pp. 775-798.

Carpo, M. (2011), *The Alphabet and the algorithm*, The MIT Press, USA.

Celani, G. (2012), “Digital Fabrication Laboratories: Pedagogy and Impacts of Architectural Education”, *Nexus Network Journal*, Vol. 14 No. 3, pp. 469-482. https://doi.org/10.1007/s00004-012-0120-x

Chen, C.-C. and Crilly, N. (2016), From modularity to emergence: A primer on the design and science of complex systems (Technical Report CUED/C-EDC/TR.166), University of Cambridge, Department of Engineering, Cambridge, UK.

Christensen, K.S. and Iversen, O.S. (2017), “Articulations on form properties and action-function couplings of maker technologies in children’s education”, *Entertainment Computing*, Vol. 18 No. 1, pp. 41-54. https://doi.org/10.1016/j.entcom.2016.09.001

Chu, S.L., Angello, G., Saenz, M. and Francis, Q. (2017), “Fun in Making: Understanding the experience of fun and learning through curriculum-based Making in the elementary school classroom”, *Entertainment Computing*, Vol. 18 No. 1, pp. 31-40. https://doi.org/10.1016/j.entcom.2016.08.007

Deleuze, G. and Guattari, F. (1980), *A thousand plateaus: capitalism and schizophrenia*, University of Minnesota Press, Minneapolis.

Dewey, J. (1934), *Art as Experience*, Minton, Balch & Company, New York.

Dörfler, K., Sandy, T., Giftthaler, M., Gramazio, F., Kohler, M. and Buchli, J. (2016), “Mobile Robotic Brickwork - Automation of a Discrete Robotic Fabrication Process Using an Autonomous Mobile Robot”, *Proceedings of Rob/Arch 2016 / the 3rd International Conference on Robotic Fabrication, Art and Design, Sydney, Australia, March 15-19, 2016,* Springer, Cham, pp. 204-217. https://doi.org/10.1007/978-3-319-26378-6_15

Dorst, K. and Cross, N. (2001), “Creativity in the design process: co-evolution of problem–solution”, *Design Studies*, Vol. 22 No. 5, pp. 425-437. https://doi.org/10.1016/S0142-694X(01)00009-6

El-Zanfaly, D. (2015), “[I3] Imitation, Iteration and Improvisation: Embodied interaction in making and learning”, *Design Studies*, Vol. 41, pp. 79-109. https://doi.org/10.1016/j.destud.2015.09.002

Ford, S. and Despeisse, M. (2016), “Additive manufacturing and sustainability: an exploratory study of the advantages and challenges”, *Journal of Cleaner Production*, Vol. 137, pp. 1573-1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Gero, J.S. (1996), “Creativity, emergence and evolution in design”, *Knowledge-Based Systems*, Vol. 9 No. 7, pp. 435-448. https://doi.org/10.1016/S0950-7051(96)01054-4

Harrison, L., Earl, C. and Eckert, C. (2015), “Exploratory making: Shape, structure and motion”, *Design Studies*, Vol. 41, pp. 51-78. https://doi.org/10.1016/j.destud.2015.08.003

Heidegger, M. (1977), *The question concerning technology and other essays*, Harper & Row, USA.

Heidegger, M. (1982), *Parmenides*, Indiana University Press, USA.

Holzer, D. (2008), “Embracing the Post-digital”, *Proceedings of the first International Conference on Critical Digital: What matter(s)?*, Harvard University Graduate School of Design, Cambridge, pp. 17-22.

Ingold, T. (2013), *Making: Anthropology, Archaeology, Art, and Architecture*, Routledge, London. https://doi.org/10.4324/9780203559055

Jankovic, L. (2012), “An Emergence-based Approach to Designing”, *The Design Journal*, Vol. 15 No. 3, pp. 325-346. https://doi.org/10.2752/175630612X13330186684150

Knight, T. and Stiny, G. (2001), “Classical and non-classical computation”, *Architectural research quarterly*, Vol. 5 No. 4, pp. 335-372. https://doi.org/10.1017/s1359135502001410

Kolarevic, B. (2004), *Architecture in the Digital Age: Design and Manufacturing*, Taylor & Francis, London. https://doi.org/10.4324/9780203634561

Langrish, J. (2016), “The Design Methods Movement: From Optimism to Darwinism”, *Proceedings of DRS 2016 / Design + Research + Society Future-Focused Thinking, the 50th Anniversary International Conference, Vol. 1, Brighton, UK, June 27-30, 2016,* The Design Research Society, London, pp. 51-65. https://doi.org/10.21606/drs.2016.222

Latour, B. (1987), *Science in Action: How to Follow Scientists and Engineers Through Society*, Harvard University Press, Cambridge.

Law, J. (1991), *A Sociology of Monsters: Essays on Power, Technology, and Domination*, Routledge, London.

Le Corbusier (1947), *The City of Tomorrow and Its Planning*, The Architectural Press, London.

Marenko, B. (2015), “When making becomes divination: Uncertainty and contingency in computational glitch-events”, *Design Studies*, Vol. 41 No. 1, pp. 110-125. https://doi.org/10.1016/j.destud.2015.08.004

McCullough, M. (1998), *Abstracting Craft: The Practiced Digital Hand*, MIT Press, Cambridge, MA.

Mead, G.H. (1932), *The Philosophy of the Present*, Open Court, LaSalle, Illinois.

Mellis, D.A. (2015), “Personal Manufacturing in the Digital Age”, In: Gibb, A. (Ed.), *Building Open Source Hardware: DIY Manufacturing for Hackers and Makers*, Addison-Wesley Professional, USA, pp. 153-166.

OED (2017), *Design*. [online] Oxford English Dictionary. Available at: http://www.oed.com/view/Entry/50840?rskey=jQD6IU&result=1#eid (accessed 09.12.2017).

Oxman, R. (2006), “Theory and design in the first digital age”, *Design Studies*, Vol. 27 No. 3, pp. 229-265. https://doi.org/10.1016/j.destud.2005.11.002

Papavlasopoulou, S., Giannakos, M.N. and Jaccheri, L. (2016), "Empirical studies on the Maker Movement, a promising approach to learning: A literature review", *Entertainment Computing*, Vol. 18 No. 1, pp. 55-78. https://doi.org/10.1016/j.entcom.2016.09.002

Petrich, M., Wilkinson, K. and Bevan, B. (2013), "It looks like fun, but are they learning?", In: Honey, M. and Kanter, D.E. (Eds.), *Design, Make, Play: Growing the Next Generation of STEM Innovators*, Routledge, New York, pp. 50-70. https://doi.org/10.4324/9780203108352

Philpott, R. (2012), "Crafting innovation: The intersection of craft and technology in the production of contemporary textiles", *Craft Research*, Vol. 3 No. 1, pp. 53-74. https://doi.org/10.1386/crre.3.1.53_1

Pinochet, D. (2016), "Making - Gestures: Continuous design through real time Human Machine interaction", *Proceedings of CAADRIA '16 / Living Systems and Micro-Utopias: Towards Continuous Designing, the 21st International Conference on Computer-Aided Architectural Design Research in Asia, Melbourne, Australia, March 30 - April 2, 2016,* CAADRIA, Hong-Kong, pp. 281-290.

Preston, B. (2012), *A philosophy of material culture: Action, function, and mind*, Routledge, London, New York.

Pye, D. (1968), *The Nature and Art of Workmanship*, Herbert Press, London.

Ratto, M. and Ree, R. (2012), "Materializing information: 3D printing and social change", *First Monday*, Vol. 17 No. 7. https://doi.org/10.5210/fm.v17i7.3968

Resnick, M. and Rosenbaum, E. (2013), "Designing for Tinkerability", In: Honey, M. and Kanter, D. (Eds.), *Design, Make, Play: Growing the Next Generation of STEM Innovators*, Routledge, New York, London, pp. 163-181.

Rifkin, J. (2011), *The third Industrial Revolution: How Lateral Power is Transforming Energy, the Economy, and the World*, Palgrave Macmillan, New York.

Sass, L. and Oxman, R. (2006), "Materializing design: the implications of rapid prototyping in digital design", *Design Studies*, Vol. 27 No. 3, pp. 325–355. https://doi.org/10.1016/j.destud.2005.11.009

Sato, K. and Matsuoka, Y. (2009), "Emergent Design and Optimum Design in the Design Process", *Proceedings of IASDR 2009 / the 3rd International Congress of International Association of Societies of Design Research, Seoul, Korea, October 18-22, 2009,* pp. 2767-2775.

Saunders, R. and Gero, J.S. (2000), "The importance of being emergent", *Proceedings of Artificial Intelligence in Design*.

Schon, D.A. (1983), *The reflective practitioner: how professionals think in action*, Basic Books, New York.

Schon, D.A. (1992), "Designing as reflective conversation with the materials of a design situation", *Research in Engineering Design*, Vol. 3 No. 3, pp. 131-147. https://doi.org/10.1007/bf01580516

Simon, H.A. (2008), *The Sciences of the Artificial*, MIT Press, Cambridge, MA.

Simondon, G. (2006), *Cours Sur la Perception: 1964-1965*, Les Èditions de la Transparence, Chatou.

Stolterman, E. (1994), "Guidelines or aesthetics: design learning strategies", *Design Studies,* Vol. 15 No. 4, pp. 448-458. https://doi.org/10.1016/0142-694x(94)90007-8

Suchman, L. (2006), *Human Machine Reconfigurations*, Cambridge University Press, New York.

Tegano, D.W. (1990), "Relationship of Tolerance of Ambiguity and Playfulness to Creativity", *Psychological Reports*, Vol. 66 No. 3, pp. 1047-1056. https://doi.org/10.2466/pr0.1990.66.3.1047

Toh, C.A. (2014), Creativity in Engineering Design: Understanding the Factors that Influence Creative Idea Development, Master thesis, The Pennsylvania State University.

Van Alstyne, G. and Logan, R.K. (2007), "Designing for emergence and innovation: redesigning design", *Artifact*, Vol. 1 No. 2, pp. 120-129. https://doi.org/10.1080/17493460601110525

Vidal, R., Mulet, E. and Gómez-Senent, E. (2004), "Effectiveness of the means of expression in creative problem-solving in design groups", *Journal of Engineering Design*, Vol. 15 No. 3, pp. 285-298. https://doi.org/10.1080/09544820410001697587

Vossoughi, S. and Bevan, B. (2014), Making and tinkering: A review of the literature, National Research Council Committee on Out of School Time STEM, Washington, DC.

Willis, K.D., Xu, C., Wu, K.-J., Levin, G. and Gross, M.D. (2011), "Interactive fabrication: new interfaces for digital fabrication", *Proceedings of TEI '11 / the 5th International Conference on Tangible, Embedded, and Embodied Interaction, Funchal, Portugal, January 22-26, 2011,* ACM, New York, pp. 69-72. https://doi.org/10.1145/1935701.1935716

Youmans, R. and Ohlsson, S. (2005), "Training produces suboptimal adaptation to redundant instrument failure in a simulated human-machine interface", *Proceedings of CogSci 2005 / the Twenty-Seventh Annual Conference of the Cognitive Science Society, Stresa, Italy, July 21-23, 2005*, Lawrence Erlbaum Associates, Mahwah, New Jersey, pp. 2416-2421.

Lucia Corsini, Doctoral Researcher
University of Cambridge, Institute for Manufacturing, Engineering Department
10 Dunbar Road, N22 5BE London, United Kingdom
Email: lc500@cam.ac.uk