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AN EXPLORATORY STUDY INTO THE IMPACT OF NEW DIGITAL DESIGN AND MANUFACTURING TOOLS ON THE DESIGN PROCESS

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Abstract

The study aims to understand the impact of new digital design and manufacturing tools on the design process. Digital manufacturing technologies are having far reaching impacts on design, however there is currently little understanding about how this is affecting the design process. The paper reports on an interview study with twelve designers who use new digital manufacturing tools, in architecture, ceramic design, product design and jewellery design. Data is gathered and analysed using a grounded theory approach. The study shows that the design process is defined by the relationships between digital design tools, digital manufacturing tools and digitally manufactured objects. The nature of these relationships vary in direction and degree of formalisation, and they are discovered to influence three key factors in the design process: (1) emergence and control; (2) creativity and, (3) design skills. The study provides new insight into the design process, as well as providing an integrated view of digital design and digital manufacture, identifying areas for further research.

Keywords: Design process, Technology, Design learning, Creativity, Uncertainty

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1 INTRODUCTION

The rapid growth of new digital manufacturing tools is expanding the boundaries of design potential. In product design, greater design freedom enables the creation of novel forms (Ford and Despeisse, 2016). In jewellery, digital tools support the production of flexible, mass customisable designs (Dean and Pei, 2012). In architecture, the integration of new digital manufacturing tools is impacting design and construction. Kolarevic (2001) points out the trend towards free form and isomorphic architectures; Hager et al. (2016) examine the sustainability benefits of additive manufacturing in construction; and Vasquez and Jabi (2015) propose new construction methods using robotics.

In parallel to these new technologies, there is a need to understand how new digital manufacturing tools are affecting the creative design process. The focus of the study is limited to the design process associated with the "digital fabrication revolution" defined by Gershenfeld (2012), in which the designer is directly engaged with making. The following research should not be viewed in terms of the design process for engineering design as defined by Pahl et al. (2013). Unlike Chryssolouris et al. (2008), who consider a range of IT provisions as part of digital manufacturing, this study focuses specifically on digital manufacturing *tools*, namely: additive manufacturing, laser cutting and CNC milling. In particular, understanding the processes associated with new digital manufacturing tools is relevant for designer support and design education.

A considerable body of research explores the ways in which digital design tools are impacting the design process, in the stages of concept generation and representation. There is, however, a gap in understanding of the role of digital manufacturing tools in the manufacturing stage. Sass and Oxman (2006) present a starting point for integrating digital manufacturing tools into a methodological design framework. The research defines a model for Digital Design Fabrication (DDF), a continuous process that integrates digital design and digital fabrication, in contrast to the discrete procedural stages in the traditional design model. It is proposed that through interaction with physical artefacts, the designer is able to expand learning in the digital design environment. The model provides an initial view of how "rapid prototyping" might be included in a design methodology. Yet the research falls short at recognising manufacturing as an integral part of the design process, and rather views the role of digital manufacturing tools as a facilitator for a paperless digital design process. The current research intends to address this knowledge gap by undertaking an exploratory study into the practice of designers. As the territory is quickly changing and there is relatively sparse precedent, an inductive approach is taken, to explore how the use of new digital manufacturing tools is impacting the design process.

The paper is structured as follows. First, an explanation of the methodological approach taken in the research. Second, a presentation of the research findings, which are highlighted in four key themes. Third, a discussion of the relationships between the themes, in the context of existing theory. Finally, a review of the implications of the findings for design research, practice and education, as well as proposed areas of research for further qualitative and experimental study.

2 METHOD

The following research adopts a grounded theory approach (Corbin and Strauss, 1990). Grounded theory uses inductive logic, starting with empirical data as opposed to existing literature. As the impact of new digital manufacturing tools on the design process in the context of the "digital fabrication revolution" has not been widely studied, this method is selected as a suitable approach for building theory. The method used seeks to gather data from in-depth interviews to generate theory which is both relevant and significant for designers.

Twelve designers, from across the following design sectors were interviewed using semi-structured interviews: architecture; product design; ceramic design; and jewellery design. Eleven out of twelve designers were European. Participants were shortlisted based on the criteria that they used new digital manufacturing tools to create their designs. They were identified through online searches and visibility on design sites such as Dezeen. Participants were selected based on availability, to reflect a range of three-dimensional design sectors, as well as including views from industry and research. All the designers had over eight years of design experience.

Three interviews were conducted using in-depth email interviews; two interviews were conducted face-to-face at the participants' studio or office, which were documented with detailed note-taking and photographs; and the remaining seven interviews took place by Skype, which were audio recorded and

complemented with note-taking. Each audio recording took place with the participants' consent and was transcribed verbatim afterwards. All the interviews were conducted by the first author and on average each interview took one hour. The interview was guided by thematic questions grouped in three sections. Firstly, the designer was asked about their experience using digital manufacturing tools. Secondly, the designer was encouraged to describe the design process for a recent project. Finally, the designer was asked to reflect on the impact of using digital tools on their design skills. Before each interview, the participants were informed about the purpose of the study. At the end of the interview, the participants had the opportunity to add information, which they thought was relevant.
The interviews were analysed using a systematic process of defining categories and identifying relationships between categories (Daengbuppha et al., 2006). Initially, *open coding* was applied to the data, by analysing key themes from the transcripts. While reviewing the transcripts line by line, the codes were gradually developed. Coding started as soon as the first interview was completed, such that emerging themes could guide questions in the remaining interviews. After all the open codes were completed, a process of grouping conceptually similar codes took place, in *axial coding*. For example, 'exploration of tools', 'iterative tool development' and 'observing problems with tools' formed the higher category 'tool making'. Finally, *selective coding* was undertaken to systematically examine and compare relationships from open coding and axial coding.

3 RESULTS

The main themes that resulted from the analysis are here described under four headings: (1) relationships between digital design and digitally manufactured objects; (2) relationships between digital design and manufacturing tools; (3) relationships between digitally manufactured objects and manufacturing tools; and, (4) digital and non-digital design and manufacturing tools. These themes are descriptive of the design process associated with new digital manufacturing technologies. Each theme is divided into sub-themes, which are exemplified by "power quotes" from the data (Pratt, 2009). Finally, the relationships between the themes are discussed.

3.1 Relationships between digital design and digitally manufactured objects

The designers spoke extensively about the *information flow* between the digital design and digitally manufactured objects. Their descriptions of this relationship drew attention to two key actions which affect the flow of information: *seeing* and *making*.

3.1.1 Information Flow

The bi-directional flow of information between the digital design and the digitally manufactured object is identified as an important facilitator in the design process. Designers discuss the desire to create a feedback loop between the physical and the digital environment, therefore closing the gap between design and manufacturing. Experience of products in the physical environment is seen as integral to learning and development. The nature of the information flow between the physical and digital varies across different designers' practice, however the process is viewed as being iterative and continuous. In some cases, designers actively reference physical outcomes to guide their designs. "*So through making things and having actual physical objects that I can now reference, that has really helped me to refine the work and develop it down the road that is getting better and better… I might go back to a previous piece, and think what did I like about that… so there is a lot of to-ing and fro-ing from the actual things to the designs*." — L
In other cases, designers rely on their previous experience of the physical environment to enable an implicit cognitive interpretation process. "*Because I have a pretty good understanding of a 3D form, I'm able to translate what I see on the screen… even though I'm working in this virtual world, I know there is just so much more than what you can see on the screen, because there just always is*." — B

3.1.2 Seeing

The frustrations associated with the translation process between the digital design and the physical outcome were widely spoken about, supporting the view that currently there is an imperfect flow of information. Many designers cite a disconnect between what they see on screen, compared with the physical outcome. Designers rely on their ability to visualise multiple 2D images simultaneously to mentally construct a 3D model, however this is an imperfect model of seeing.

"*You spend a lot of time agonising, tumbling things round on screen trying to get an appreciation of what things will be like, but to be honest with you, there is still a moment of surprise, when you get the part out and you think, 'oh, this is what it's really like'.*" — J

"*I'll get the design as far as I can, by just [laser] printing out different views of it and thinking whether it's going to work by turning it around on the computer.*" — L

Through experience designers can learn how to adjust their modes of seeing, suggesting that this cognitive translation skill depends on learning and knowledge. "*I know because of the shrinkage factor that it will shrink about 17% vertically and 12% horizontally. I just slightly distort the drawings on screen to compensate, just by eye… I realised they were coming out a bit stubby.*" — C

The benefits associated with eliminating information loss are significant for quality improvement and error reduction. In layer-by-layer additive manufacturing, the digital design is converted into layered sections before it is physically printed. This translation process presents a dimension of information loss. An attempt to eliminate this translation process in additive manufacturing is undertaken by Designer H. Designer H seeks to achieve a direct relationship between the digital and physical, by designing a process of digital simulation to mirror the manufacturing process. The approach sets precedent for how the closer integration of design and manufacture can enable a closer relationship between the physical and the digital. "*The design becomes parallel to the manufacture… you can build with freedom, see how it should be, there is less interpretation and less things can go wrong.*" — H

3.1.3 Making

Although there has been much discussion about the democratising force of digital manufacturing tools, access to tools is often still prohibited by cost and limited knowledge about the processes. It is clear that for some designers, with more restricted access to tools, there is a growing divide between design and making. Seven out of the twelve designers interviewed use bureau services to manufacture their designs. As a result, these designers tend to distance themselves from the manufacturing process, drawing clear lines between design and making.

"*Digital manufacturing allows me to design without actually making.*" — K

"*I design everything in a computer programme, I email it off to a RP manufacturer, it's like a bureau service so they print it in wax and send it to a caster, so I don't ever touch my waxes anymore.*" — L

Many of these designers acknowledge the additional design challenges this presents. "*I have to be pretty confident that when the bureau presses go, that's what I want, because it's so expensive.*" — B

However, they cite the importance of relationships with bureaus to navigate the uncertainties associated with fabrication. "*The relationship with the bureau, is really, really important… working with their technicians is fundamental… It's a relationship that needs to be developed because they are busy making objects for aerospace or medical and what I'm doing is just as different as any of those industries and they have to understand what I want.*" — B

In contrast, designers who have access to their own tools emphasise the importance of making as a way of learning, discovering new designs and expanding design possibilities. The belief that making can simplify the design process is also expressed. By allowing for contingency in the making process, and adopting an iterative approach, it is no longer necessary to achieve a completely perfect design.

"*We really like to make this stuff ourselves and it's difficult if you have to rely on other people, it costs money and time and you have to make very precise drawings, while if we do it in our own studio you can just do, and do it again, change it. It's a simpler process.*" — D

"*You design something, you print, you go back to the computer, you modify, every time you go back to the computer.*" — E

The opportunity for designers to engage with making challenges the traditional role of the designer, particularly in architecture, which exhibits a highly-mediated design process. Consequently, making encourages the creation of designs which truly consider the full cycle of the design process. "*There is a shift in architecture, to design for manufacture, thanks to digital manufacturing. Traditionally there are many process steps, and often there are lots of things which can get lost. It becomes difficult to build, because no one understands it.*" — H

3.2 Relationships between digital design and manufacturing tools

The capabilities of new *digital manufacturing tools inform design* by expanding design possibilities. In response, the designer must adopt new ways of thinking to exploit the new manufacturing tools. Consequently, it is suggested that new *digital manufacturing tools inform designer thinking*.

3.2.1 Digital manufacturing tools inform design

To some extent, all of the designers interviewed spoke about the use of new digital manufacturing tools as enabling the design of the previously impossible. Designers discussed how they adapted designs to respond to the constraints of the manufacturing tools. "*We understood if you start to use 3D printing and ceramics it's better to start designing with more scaffolds… structural pieces instead of single walled pieces. So in a way, the process just tells you something about how to design.*" — D

In some cases, digital manufacturing tools not only define design constraints but also provide stimulus for design inspiration. "*There are these fine lines that are characteristic of wax 3D printed pieces... that's all used quite strongly as an aesthetic in the work... I don't file that off, I use it. I might do things like in the actual modelling process, angle facets so that those lines do something different… so there are some quite nice elements of teasing out these processes in the machine marks*." — L

3.2.2 Digital manufacturing tools inform the designer thinking

The use of new digital manufacturing tools means designers must reconsider their design approach. Rather than doing things as they always have been done, new modes of thinking and engagement are needed, such that designers can maximise the potential that the new manufacturing tools offer. "*Why not take the opportunity to build in a way that is more efficient, because you can design in a way that saves more material, using much more porous structures to get super performance*." — F

Designer G identifies the problem that designers do not give enough consideration to the needs they are designing for, when using digital manufacturing tools. The designer speaks repeatedly about the need to let go of old ways of thinking, and to consider design from a network approach. In particular, this places a renewed focus on the brief definition stage of the design process. "*We took a step back so we really considered this node, the function of the node as part of the overall context...the interactions between different functions... taking one step back and thinking what that node would be doing was important*." — G

The integration of computational design methods and digital manufacturing tools, is perhaps having the most significant impact on designer thinking. Notably, among the architects interviewed, there is a marked shift in design methods, moving from representational, CAD based design to computational, generative design. The trend has been facilitated by the growth in computational power, however, is only recently being made feasible in the physical environment through significant improvements to digital manufacturing tools. "*The first subdivided column took 200 hours to fabricate. Today the firm Highcon can reproduce the identical column in 10 hours*." — I

As well as requiring designers to explicitly learn new skills like coding, the designer is required to formalise their design process, which presents a new challenge.

"*Modelling something is subjective, it's artistic but when you are modelling behaviours you have to consider the design behind the form so it challenges the designer into thinking into deeper levels of what that form represents and how it is generated*." — F

"*How do you quantify design? Because design is something you can't really see or explain, it's something that you just know*." — H

3.3 Relationships between digitally manufactured objects and manufacturing tools

There exists a new phenomenon of designers who directly engage between digitally manufactured objects and digital manufacturing tools. This engagement takes place in the form of *tool making*, where the designer actively develops and builds tools to design physical outcomes. Another relationship emerging between digitally manufactured objects and manufacturing tools, is as a result of robotic *sensing*, where feedback from physical outcomes is sent to manufacturing tools in real time.

3.3.1 Tool making: making and adapting machines for digital manufacture

Five of the designers interviewed were involved in tool making. Examples of tools include a 3D printer for ceramics and a large scale free form additive manufacturing process. Designers are driven by the motivation to overcome the design constraints of current tools. Interaction with tool making offers designers the opportunity to reflect and observe new limitations. Exploring problems forms the basis of an iterative approach to building and developing the tools. In this way, the relationship between the digitally manufactured object and the manufacturing tool is strengthened. By reflecting, and evaluating the physical outcomes, the designer identifies new design aspirations and new manufacturing problems. Inspiration by analogy reveals new ways of developing manufacturing tools.

"*It's a parallel process. First I have to make a machine, that can make something, an object. But it always starts with 'Okay, what do I want to make that is not possible yet?' So then you make a prototype, you modify the machine, you make an object, so it's an interaction. You are constantly going between the object and the machine… sometimes I do the design in just a couple of hours…I'm more interested in the process behind the object than the object itself.*" — E

"*There was this guy… who was working on this frosting machine for cakes. And so we took that as a basis and then we put clay in it and did a lot of tests… We were very frustrated that you can't start and stop the printer… so we were working a lot with air pressure… You don't see the limits of the machine if you don't have it next to you*." — D

3.3.2 Sensing

Taking a more radical approach, digital manufacturing tools have the potential to directly facilitate the information flow between the physical outcome and digital manufacturing tools, bypassing the designer entirely. Designer F uses visual sensors to monitor and control the additive manufacturing process, thereby creating an explicit feedback loop between the physical and digital. "*We attached a camera on the robotic arm so that the robot was constantly monitoring what had been printed so far... it was 4D scanning what was there in the physical world and comparing that to the digital world. If there are slight mismatches, which is always the case, because we can't design with 100% accuracy in the computer, we use this new materialised form as the input for the next layer*." — F

3.4 Digital and non-digital design and manufacturing tools

The designers spoke at length about the differences between non-digital and digital design tools. In particular, three key themes relevant to this discussion were discovered: *emergence and control*, *creativity*, and *design skills*.

3.4.1 Emergence and control

The balance between emergence and control is constantly being navigated in the design process and presents a number of challenges for designers. It is recognised that in some cases, a more limited design brief necessitates a more controlled approach. Yet, the use of error in design can also provide design inspiration and expand possibilities. Designer D, highlights the purposeful provocation of errors to discover new designs: "*We start to build things to provoke errors*." — D

The extent to which the use of digital tools is perceived to influence emergence and control varies among the designers. Some designers suggest that digital tools result in more rigid outcomes: "*I find the software to be less forgiving and quite structured in its outcomes*." — A

Whereas other designers highlight the flexibility of the digital tools: "*When I'm not happy with a direction I've chosen, I can go back to a previous version with a few clicks and start over*." — K

Clearly, there is the potential for digital design tools to support the design of multiple variations at little additional effort. This shifts design emphasis away from plan-based to parameter-based design. "*Rather than the traditional idea of a singular solution and working out some idealised solution it's more about a solution base of possible outcomes*." — J

In particular, there are new challenges for managing emergence and control in generative design methods. The designer determines the code, yet may not pre-determine the resulting design. The designer adopts a new role as a "curator of emergence", in which they are responsible for ensuring that the outcome is compatible with the design parameters. "*The challenge is to find a balance between sufficient control and the possibility of the unexpected… while processes are deterministic and thus reproducible, every detail may no longer be directly foreseeable, and not specifiable in a traditional sense. Thus, there may be an element of surprise, this is something we can embrace and nurture*." — I

The tension between emergence and control also exists in the manufacturing stage of the design process. Designer F describes how changes to environmental factors in additive manufacturing can impact the build outcome. However, by manufacturing with increased error tolerance, process improvements can be achieved in terms of speed. It is clear that by foregoing some elements of control, significant design benefits can be achieved. "*So if you increase the error tolerance, you give some tolerance and make sure that the structure cannot collapse, you can go much faster*." — F

3.4.2 Creativity

The designers are clear in their belief that digital manufacturing tools advance creativity, providing an additional tool with which to experiment. New possibilities for design ideas offer creative inspiration. "*The technology and its possibilities are amazing, endless, inspiring on so many levels. It provides the ability to produce works that were previously unthinkable*." — A

On the other hand, there seems to be a conflict between digital design tools and creativity. Designers perceive the digital interface to be unintuitive, boring and time consuming. Consequently, the use of digital design tools poses a genuine challenge for design. How might it be possible to support creativity at all stages of the design process using digital manufacturing tools?

"*I can't just look at a computer screen all the time. I might print something out [on paper] and then rework it by hand if I think it's just not quite right, it's always a two-way relationship*." — L

"*The logical process of writing a computer program is arguably different from the more immediate approach of drawing with a pencil. In the former, we often forfeit the notion of the gesture. The most interesting results may appear when we succeed in integrating these separate approaches*." — I

3.4.3 Design skills

The introduction of new digital manufacturing tools demands that designers have greater fluency in digital design skills. Designers are required not only to explicitly learn skills such as CAD or coding but are required to think differently about how they express their designs. Additionally, designers may be required to become more interdisciplinary as the design process becomes more integrated. "*It's really important to start mixing up our designers. Product designers should be doing architecture and architects, well they are already doing chairs, but they should be doing other stuff as well.*" — G

Several designers express frustrations at the challenges of learning new digital skills. They are also mostly self-taught, pointing towards a gap in design education. Notably, two designers describe the opposition they faced from design institutions when using digital manufacturing tools while studying. Perhaps offering some explanation for this, Designer J describes the fear that students will become too reliant on digital tools. "*It's very dangerous to not have an analogue background... you can be a slave to the technology… I have students who queue up to use a laser cutter when there's a band saw right next door*." — J

Learning in a physical environment is viewed as being important to designer education. Unanimously, all the designers believe that digital skills are not a replacement for non-digital skills, however only a few still hand sketch ideas before using digital tools. Mostly, it is suggested that hand sketching is time intensive and insufficient for capturing the level of complexity desired. It is repeatedly suggested by designers that their tacit experience of a material or craft, enables them to achieve designs using digital tools, which a novice would struggle to produce. Additionally, it is suggested that for an experienced designer, there is greater capacity for mental problem-solving, such that hand sketching or model making are less important for resolving ideas. "*I have 25 plus years of making pots so I hope that informs what I am doing… I think it's fundamental for students or anyone starting out in this world to experience materials and processes first hand… it just informs your thinking so much, there's that engagement and that problems solving when you are engaging with material and evidence*." — B

4 DISCUSSION

The main focus of the study has been on understanding how digital manufacturing tools influence the design process associated with the "digital fabrication revolution". The study indicates that the design process is defined by the relationship between three key elements: digital design tools, digital manufacturing tools, and digitally manufactured objects. The relationships between these elements are impacting: (1) emergence and control; (2) creativity; and, (3) design skills. The findings are summarised and illustrated in Figure 1. In particular, the model identifies implicit and explicit relationships between the elements. Explicit relationships are defined by formalised representations of information, whereas implicit relationships are defined by unformalised, cognitive design processes which are actioned by the designer. Implicit processes are typically iterative and continuous activities. Overall, the study broadens knowledge on design by offering a model to describe the various factors in the design process. Additionally, the study provides perspectives on the use of digital manufacturing tools, focussing on designer practice and attitudes.

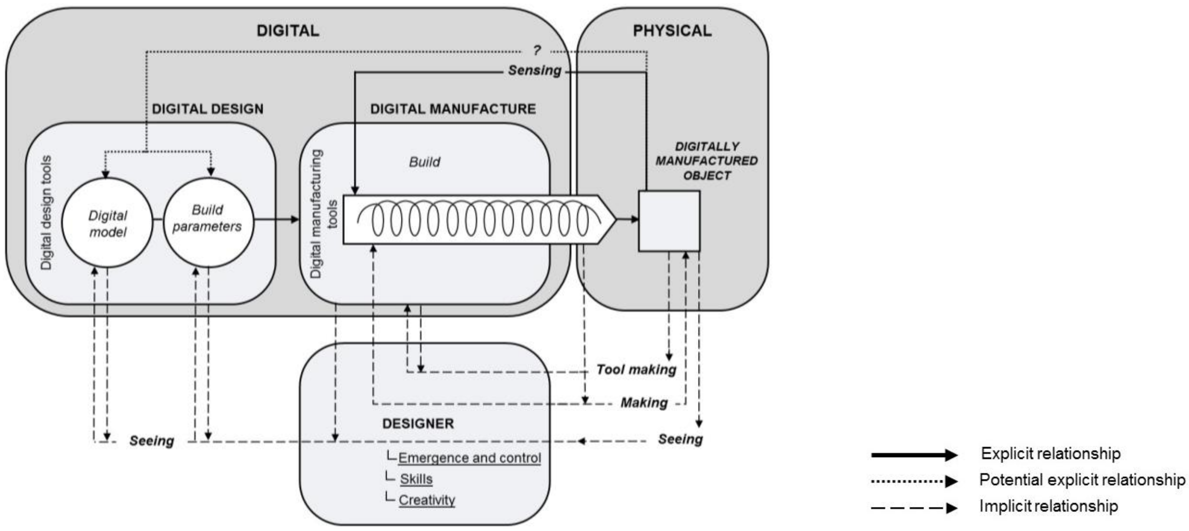

Figure 1. Relationships in the design process

As well as providing new insights, the study adds qualitative description to existing studies on design. While the study does not go as far as Gürsoy and Özkar (2015) to suggest that making is an integral part of the design process, it highlights that *making* provides an opportunity to narrow the gap between the digital and physical. The study shows that although the relationships from *digital design to digital manufacture to digitally manufactured object* are already explicit, making reinforces this relationship. The importance of making is highlighted by El-Zanfaly (2015) who observes that the separation between design and making impacts the work of students, limiting concept generation and learning. Harrison et al. (2015) present an experimental study for making kinematic parts, where evaluation of the physical model enables the design of generative rules, thus demonstrating the relationship: *seeing*. Harrison et al. (2015) point out the bi-directional information flow which takes place between the physical and digital design, also observed by Oxman (2006). The proposed model adds more depth to understanding the nature of this relationship in the design process.

Beyond making, the study highlights the role of *tool making* in the digital design process. The proposition of the designer as a tool maker is noted by Aish (2003) in the context of software design. Aish posits that a creative tool is one that can be customised to applications that extend beyond the original intention. Building on this supposition, the process of tool making can be viewed as a significant method of expanding creativity in design, by which increasing the capability of manufacturing tools, in turn increases the potential for digital designs. Research is needed to understand how tool making might be used to facilitate learning.

Additionally, the model highlights that the only explicit feedback from the *digitally manufactured object* takes place when *sensing* is employed to directly adjust build parameters. Experimental research that demonstrates the use of sensing can be found in Doerfler et al. (2014). The research documents a large scale additive manufacturing construction technique, using robotics to remotely project loam blocks. Rather than building according to a pre-determined design, design parameters are set for and sensors monitor the structure during construction, providing feedback to the robots, such that the robots' settings can be adjusted. Reflecting on the concept of explicating feedback, the present study questions whether it is possible to make other relationships in the process explicit and as a result eliminate information loss. There is potential for explicit feedback from the *digitally manufactured object to the digital design*. In light of advancing technologies, such as artificial intelligence, it is questioned whether the formalisation of this relationship may become possible.

The thematic analysis also revealed a number of factors, which are influenced by relationships in the design process. The balance between explicit and implicit processes in the digital design are manifested in the theme of *emergence and control*. Historically, it has been suggested that digital tools impose high levels of control, whereas non-digital tools allow for more exploratory design and elements of surprise (Marenko, 2015). The study contradicts this view by demonstrating that the use of digital tools is compatible with an emergent design process. This corresponds with experimental findings from Knight and Stiny (2001) and Cannaerts (2009) who conclude that digital design can generate emergent results. Oxman (2006) points out that there is a move towards non-deterministic design processes, citing the use of generative and parameter-based design. Indeed, many of the designers identify that design does not develop along a single pre-determined trajectory, but must respond to situated factors, resulting in a range of possible ideas (Harrison et al., 2015). The notion of purposefully provoking errors to create new ideas is reflected in literature about uncertainty, ambiguity and creativity (Marenko, 2015). Further research is needed to understand how the concept of provoking 'error' might be embedded into new digital manufacturing processes.

The study adds to existing research on the implications of digital tools on *skill* and *creativity*. While the designers spoke about the creative potential of digital manufacturing tools, they expressed the belief that digital design tools were restrictive, supporting research which suggests that digital tools encourage design fixation and restrict the reinterpretation of new ideas (Stones and Cassidy, 2010). Consequently, the use of digital design tools poses a genuine challenge for design, raising the question: how might creativity be supported at all stages of the design process using digital manufacturing tools? Of note, Cannaerts (2009) postulates that one of the reasons for less creativity among students using digital tools is that they do not have the skills necessary to fully engage with digital tools. This draws attention to the evolution of design skills needed to respond to the growth of new digital manufacturing tools. As well as explicitly learning new skills, designers must adapt to new ways of thinking to express their ideas. Further research is needed to understand the influence of physical experience in affecting the creativity of designers using digital manufacturing tools.

5 CONCLUSION

The disjointed view of digital design tools and digital manufacturing tools in design literature is problematic for design practice and education, as designers are not empowered to maximise the potential of new digital manufacturing tools. This research details an exploratory approach, using qualitative methods to gather and analyse data about the design process. The research develops a model, which integrates digital design tools, digital manufacturing tools and digitally manufactured objects, providing a view of the design process in the context of the "digital fabrication revolution". In particular, the model draws attention to the nature of the relationships in the model, which are defined by direction and degree of formalisation. Consequently, the model points out opportunities for improved relationships between elements in the design process, such that the loss of information, and resulting errors and inefficiencies, can be reduced. The research identified three key themes, for further research, which are influenced by the relationships in the digital design process: emergence and control; creativity; and, design skills.

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APPENDIX

Table 1. Participants

Designer	~ Team size	Design sector	Field	Tools	Design method	Interview
A	1	Ceramics	Industry	Tool user	Representation	Email
B	1	Ceramics	Industry	Tool user	Representation	Skype
C	1	Ceramics	Industry	Tool maker	Computation	Face - face
D	1	Ceramics	Industry	Tool maker	Representation	Skype
E	2-3	Ceramics	Industry	Tool maker	Representation	Skype
F	4-5	Architecture	Industry	Tool maker	Representation	Skype
G	3	Architecture	Industry	Tool user	Representation	Skype
H	< 10	Architecture	Research	Tool maker	Computation	Face - face
I	< 10	Architecture	Research	Tool user	Computation	Email
J	1	Product	Industry	Tool user	Representation	Skype
K	1	Product	Industry	Tool user	Representation	Email
L	1	Jewellery	Industry	Tool user	Representation	Skype