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Making Rules, Making Tools: How Can Shape Grammar Support Creative Making?

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Making Rules, Making Tools:

How can shape grammar support creative making?

A thesis submitted for the degree of Doctor of Philosophy

Lynne MacLachlan

BEng(hons) BDes(hons) MA(RCA)

Department of Engineering and Innovation

The Open University

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Declaration

This thesis is the result of my own research and does not include the outcome of collaborative work, except where stated otherwise. The dissertation has not been submitted in whole or in part for consideration for any other degree.

Lynne MacLachlan
The Open University
23rd January 2018

PUBLICATIONS

During the course of this study the following papers have been published:

MacLachlan, L., Earl, C., Eckert, C., 2012. Creativity in craft led design: the Tools are the rules. In *DS 73-1 Proceedings of the 2nd International Conference on Design Creativity Volume 1*. Available at:

http://www.designsociety.org/publication/32487/creativity_in_craft_led_design_the_tools_are_the_rules [Accessed June 23, 2015].

MacLachlan, L., 2014. The Creative Craft of Generative Design, In: All Makers Now Conference Proceedings 2014, Falmouth, UK. Available at:

http://www.autonomatic.org.uk/allmakersnow/all-makers-now-2014-journal/ [Accessed December 3, 2016]

MacLachlan, L and Jowers, I, 2014. Formalising flexible multi-material surfaces as weighted shapes. In: SA '14 SIGGRAPH Asia 2014 Creative Shape Modelling and Design, 3 Dec 2014, Shenzhen, China, ACM.

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FIGURES

ABSTRACT

Design theory has previously studied the practices of architects, industrial designers and engineers. Designer-makers, designers who work independently, designing and making objects with close attention to tools and materials, have not been similarly studied. A renewed interest in craft and making, in part catalysed by new computational and digital fabrication tools at designer's disposal, strengthens the case for studying successful design-through-making processes. An analogy between rules transforming shapes and tools transforming material provided the initial indication that concepts from shape grammar could be aligned with making processes, to potentially support creative making and deliver new theoretical and applied knowledge for both spheres.

The first part of the thesis examines shape grammar theory as a method of modelling designer-maker creative episodes, to inform designer practice. Evidence was gathered from interviews with designer-makers, observations from a design process carried out by the author and other literature on designer-makers. This evidence was analysed in the context of shape grammar and established creativity literature in order to seek formal descriptions of creative episodes. It was found that designer-makers used tools to define personal and shared design worlds and focussed on and undertook specific activities relating to tools which have been classified; tool selection, tool combination and tool transformation, all of which have creative potential. Tool transformation was found to have further scope for definition and it was found that designers can perform parametric, functional and reformatting transformations on tools to produce new and useful design outcomes. Shape grammar schemas were found to provide useful descriptors for the operations performed by designer-makers on tools.

The second part of the thesis inquires if shape grammar as a design method can support creative computational making, by specifically exploring the use of shape grammar weights, a way of modelling material properties alongside shape operations, as a tool for generating designs for multi-material 3D printing. A number of design reasoning and computational

making experiments were carried out and the process and results reported and considered. The outcome is a range of specified weights systems and a general schema for defining and using weights as tool for managing material properties for multi-material 3D printing that can be used and transformed by computational makers. The general weights schema also extends previous theoretical definitions of shape grammar weights. This part of the thesis also demonstrated the importance of tool development and transformation as a basis for creative episodes in design-through-making processes.

1 INTRODUCTION

The author is a designer-maker, mainly using digital tools and 3D printing to produce jewellery and objects and so has a personal experience of design that has informed the development of the research questions of this thesis. This research brings together three spheres of interest; making, creativity and shape grammar. How making, or craft, influenced the design processes of designer-makers was the initial point of inquiry for the author. Then by taking creative outcomes as the hallmark of a successful design process, activities that brought about creative episodes in designer-maker practice became a focus and way of validating the usefulness of any knowledge found. Finally shape grammar was found to have many points of correspondence with these two spheres, and hypothesis was developed that shape grammar could be used to describe and support creative making, and hence the grounding for this thesis was arrived at.

A guide to the impetus, research questions, structure, scope and terms of this thesis can be found in the following sections.

1.1 The author's background

Much of the rationale and approach for this research has arisen from the author's own experiences of designer-maker practice, education and teaching of jewellery design and making, a brief explanation of her career path to date gives a view of the how the research questions and chosen methods and methodology came to be formulated.

After a degree in Aerospace Engineering and a year working in industry, the author returned to education to study at Duncan of Jordanstone College of Art in Dundee, specialising in Jewellery and Metalwork Design. Following this she completed a Master's degree at the Royal College of Art in Goldsmithing, Silversmithing, Metalwork and Jewellery. Since then, while carrying out PhD research at the Open University, the author has continued her design practice, as a designer-maker of jewellery specialising in using and experimenting with digital

tools. During this time she has also taught undergraduate jewellery design students introductory modules on CAD software, use of digital fabrication techniques and mentored students that wished to integrate these further into their practices. These three activities have had a reciprocal influence on one another, developing ideas about digital making, both practical and theoretical.

A first degree in aerospace engineering and a year working in the space software industry turned out to be a frustrating experience. Although the author enjoyed computational based work, the disconnect between the computation and a physical objects left a feeling of dissatisfaction. On returning to art school the author selected to specialise in jewellery and metalwork; a decision based on the fact that the department had a well-equipped and intriguing workshop, where physical interaction with materials was the focus. Indeed the course was very much craft based, learning and practice took place in workshop environments, and practical, physical knowledge was transferred by live demonstrations from tutors and technicians. The academic side of this education came in the form of art and design history – lectures, reading and writing on the consideration of the philosophical concepts embodied in the work of lauded artists and designers. In the author's experience design theory was not taught formally, although this may not be the case for undergraduates everywhere of course. Producing designs that were viewed by tutors as successful as seemed almost a black art, much of the advice offered seemed to be personal opinion rather than an objective analysis, leaving the author some confusion at times about what was good or bad or why. Other than that development of creative practice was almost expected by osmosis, no strategies were offered on how to be creative, yet with hindsight the author realised creative outcomes were what the students were predominantly judged on.

The author is perhaps one of the first 'digital natives', being born just as computers were starting to be used by the general population. Having a computer scientist for a father, the author was at the advantage of having a personal computer in the home from an early age, this familiarity made computer use a natural progression for her design work. Although her work

has become increasingly digitally designed and made, the way this happens still feels very much in the realm of making and craft. The characterisation of the computer as a kind of craftsman's toolbox by Malcolm McCullough's in *Abstracting Craft: the practiced digital hand* [77] resonated with the author during her undergraduate studies and beyond. Like McCullough suggests, experimenting with digital tools and the analogue tools felt like a very similar activity.

The author's final degree work at Duncan of Jordanstone was developed from creating abstract, repetitive patterns based on drawings of insects, prototyped with laser cut card and finally made from etched silver and resin, Figure 1-1shows a bangle from the final collection. These patterns involved a lot of repetitive work on Adobe Illustrator – effectively making polar arrays by iteratively rotating a shape at polar intervals, testing different combinations of shapes and angles until a suitable arrangement was found. This process was time consuming as the software did not have a polar array tool or script integrated like other CAD software, from previous experience the author knew this laborious process was something that could be easily automated by an algorithm, beginning a curiosity about generative design.

Figure 1-1: 'Flutter' bangle, Lynne MacLachlan, silver and resin, 2008

By the end of her MA the author was trying to 'grow' designs by experimenting in parallel with analogue and digital approaches, exploring processes like growing copper sulphate crystals and casting their forms and also trying to mimic natural processes with algorithms built in Rhino3D and Grasshopper, a CAD package with an accompanying visual algorithm editor. The author

also experimented with found software such as Jenn 3D, a freeware programme which generates and manipulates visualisations of complex mathematical structures, to mimic the structure of bubbles.

On embarking on this research the author wanted to discover more about the making processes and tools that she seemingly intuitively adopted as a way of designing. It was felt that formal descriptions of designer-maker practice could help improve the chances of successful designs for the author and other designer-makers. Thus a potential line of inquiry into designer-maker practice was established.

1.2   Introduction to the research questions

This research was motivated by the author's desire to describe, understand and improve the kind of design practice she was engaged in, that of design-through making with a focus on experimenting with tools. The author's knowledge of algorithmic generative tools from her practice provided a bridge to cross reference concepts from shape grammar theory, also having a basis in generative design, with making and tools. Enquiries into craft literature and design theory research opened up a number of themes and omissions in relation to design-through making, leading to the question '*can shape grammar support creative making?*'. Two strands emerged, a theoretical strand, using shape grammar to model creative making practices, and the applied strand, applying shape grammar weights in a digital design-through-making process as a tool to generate designs, hence the two parts to this thesis.

1.3   Structure of this thesis

A description of the structure of this thesis is now presented; each chapter title is listed and accompanied with a short summary of the contents.

1Introduction: this chapter introduces the thesis by providing a summary of the author's career path to date in order to establish a view of the motivation behind this research. The

structure of the thesis is detailed here and the scope and limitations are defined. A final section lists descriptions of the key terms used throughout the thesis to further establish the locus of the research.

2 Literature review: this reviews the work done by others in several fields that are relevant to the research questions, setting a scene for the research questions. First reviewed is the relationship between craft and design in a historical context, followed by an examination of other literature relating to craft and making. This is followed by a general review of design research and a more detailed look at some relevant parts of this. Shape grammar theory plays a key role in modelling and formalising the ideas in this thesis, a review of the work done in this particular research community is also reviewed and summarised to provide a background for the reader. Also reviewed is literature relating to creativity and a specific look at recent research done on digital tools, computational making and craft. On the basis of the analysis of the literature this section concludes the chapter by presenting the research questions posed for this research.

3 Methodology and methods: A methodology chapter examines possible research methods and methodology to answer the research questions, explaining and outlining the methods selected and those rejected.

PART I: Framework for strategies for stimulating creative episodes (chapters 4-8): contains research that addresses the main research question in a theoretical way, questioning how shape grammar theory can be used to model and guide creative behaviours in design through making. This is done by analysis of interviews of designer-makers, finding comparing and contrasting practices in established design and creativity with that of the designer makers. This leads to a more focussed look at tool activities, which emerged as an important theme from the interviews. Finally shape grammar schemas are demonstrated as a way of modelling making processes and tool transformations, through discussion and the modelling of a computational-making process carried out by the author.

PART 2- A weights schema for colour 3D printing (chapters 9-12): addresses shape grammar as a design method in the context of the research question, in particular shape grammar weights as a computational method for designing and making objects for 3D printing. To do this previous shape grammar weights theory is applied to design reasoning experiments and applied computational making processes from the perspective of use for multi-material 3D printing systems. A range of scenarios are presented, resulting in a range of weights approaches and tools for two 3D printing systems, one that makes use of coloured inks to produce coated multi-coloured objects and another that blends materials to produce multi-material, multi-property objects. The result are some specific implementations for these accessible systems and an overall general weights schema extending shape grammar weights theory and offering designers a reference framework for shape grammar weights.

13 Conclusions: The concluding chapter revisits the research questions and discusses how these have been answered by the research. A discussion section explores the how the findings fit within current related research communities and the contributions to knowledge are clearly defined. Finally the summary of the thesis, some suggestions for future work and a personal reflection by the author can be found at the end of this thesis.

The thesis concludes with a bibliography and a short appendix covering the details of the questions.

1.4 Scope and limitations of the thesis

Design can be seen as a very broad field, ranging from the design of complex engineering systems to the production of objects that are appreciated as works of art. This thesis is concerned with a specific kind of design activity which can be termed 'design-through-making', carried out by those that often refer to themselves as designer-makers.

Many design courses in British art schools are still presently still run on a system broadly based on the ideas of the Bauhaus, where certain design disciplines are taught by practice of their associated craft techniques. Students learn by designing and making objects in a workshop and or studio environment, learning by practical demonstration and practice, alongside some academic, theoretical learning – lectures and essay writing. Graduates of this system go on to many different careers, but it often produces one particular kind of designer – the designer-maker.

The intention of many of these students once graduated is to work closely with their chosen tools and materials with an independent ethos, producing one off and small batch objects. They predominantly design alone, and so this thesis is not concerned with collaborative design processes. They may make their products themselves, with their tools and adapting varying degrees of automation, although outside sources may be involved in production as well. The defining feature of these designers is that they work very closely with tools and materials, designing by exploring the possibilities of these, and will understand how to make the products they design in detail, rather than producing sketches to be handed over to a manufacturer. Initially this usually entails prototyping and experimenting with tools and materials until a useful new design or technique has been found, usually in response to a design brief either formal or self-motivated, usually to access a specific design domain and audience. The designer-maker will often proceed with a certain group of tools, materials and techniques, making objects the same or with lesser or greater variations, often for many years.

The aim of the first part of this thesis is to use an examination of the role tools and materials play designer-makers creative episodes, where a new and useful discovery is made, and if ideas from shape grammar could be a relevant way of describing and supporting this. Design theory, since conception, predominately focusses on sketching and cognitive reasoning in design fields where the production of the finished object is disjointed from the design process, such as architecture, industrial and engineering design. This view of industrial design as the discipline of developing an explicit representation of an object and specification of requirements, apart from the actual physical object, can be traced back through current design theory, to Herbert Simon's book *Sciences of the Artificial* [101] and even further through design history to Alberti, who sought to make the distinction between the corporeal world and the 'mind's eye' a place where spatial construction could take place and the concepts of point, lines and planes used representations for architecture [16] and a broader tradition in philosophy of hierarchically separating mind and body. This research seeks to address not this kind of purely symbolic way of designing, but one where the designer focuses on experimentation with the material and tools to bring forth useful objects, a facet of design practice that has at times been neglected in design theory and research.

This thesis uses shape grammar theory, part of the design theory tradition and based on sketching, as a theoretical method of helping to formalise the workings of creativity in making. It is intended that shape grammar can provide a link from the world of design theory to the often enigmatic world of making and craft, due to it being rooted in visual computation rather than being linguistically based. In the most elemental description shape grammar entails transforming shapes with a given rule to create a new shape. It was found that the concept of a rule was used to describe the mechanisms of creativity by Margaret Boden [10] and the acquiring and execution of craft skills by Dormer [27], signifying strong relations between the three and offering a context to both classify and validate the findings from the first part of the research.

Of particular importance in this work is the analogy that in shape grammar rules are used to transform shapes, while the maker uses tools to transform material, this analogy opens up possibilities to use shape grammar to provide clarifications of designer activities in making. Allowing the concepts of rules and tools to become interchangeable in designer-maker practice allows a theoretical framework to be established, it is hoped this can act as a guide to designers involved in design-through-making, both in physical and digital contexts, discovering tactics that can be used to increase the likelihood of creative discoveries.

The second part of the thesis looks in another other form, the practical application of shape grammar mechanisms for actually designing. New 3D printing technologies are now readily accessible to the designer-maker, so this thesis assumes it is pertinent to try and find ways of creating designs suitable for this kind of production with the ethos of design through making in mind. Digital fabrication is a method of production that returns close control over the manipulation of material into an object to the designer, much like a traditional craft practice as opposed to an industrial design process incorporating and combining complex manufacturing techniques. Designers are increasingly using this new, increasingly accessible, technology, some purely to manufacture objects and prototypes in a conventional industrial design sense, but many are taking a more craft-like experimental approach with the hardware and the associated software.

Several types of 3D printing systems currently exist, each with an array of associated materials. This research identifies multi-material 3D printing as a particularly interesting case to explore to answer some of the research questions. A recent development in 3D printing, multi-material printing offers the opportunity to print objects with variable materials and material properties in one piece on one machine. The practical design experiments in this research make use of the two particular machines, the Z Corp colour printer, a powder binding system that uses cyan, magenta, yellow and black ink cartridges, coating the printed surface and array of colours, and the Objet Connex printer, a stereolithography system with a range of resins with different colours and properties that can be combined in one object. At the time of

experimenting and writing these were the most easily accessible to an independent designer-maker through bureau services. No doubt access and technology will change over time as 3D printing technology evolves, but it is hoped that despite focus on these particular systems much of the general findings will have relevance in the future as new multi-material techniques and machines are realised.

The computational, rule based nature of shape grammar makes it well placed for to play a role in computational making, both in a theoretical sense, the foundations of which are laid out in the first part of this thesis, but also in a more direct way; using close algorithmic interpretations of shape grammar rules in CAD based generative design tools that can in turn be linked to digital fabrication systems. Some researchers have addressed this, for example Sass [92] and Shea [98,99], both programming shape computations to generate designs for architecture. This research tackles an extension of shape grammar developed by Stiny [106,108] and Knight [59,60,61], that of applying 'weights' to shapes, to represent material properties, introducing the capability for computations associated with material properties to take place alongside shape transformations.

The idea of weights seems to align well with multi-material 3D printing, therefore investigating the possibilities of such a combination has merit. There are many ways of designing and generating structures and patterns for multi material printing, but the thesis is concerned with examining a method based using shape rules and transformations of weighted shapes. The design experiments seek to validate shape grammar weights as one appropriate system for managing variable materials in a computational making design process, where the desire is to generate objects ready for printing on such machines. Beyond this it is hoped though that examination of this specific method may reveal broader knowledge about associated theoretical issues, such as the theory of shape grammar weights, computational making and a theoretical framework about rules and tools.

1.5 Terms

A list of some specific terms used in this thesis are clarified here.

An **ambient** shape attribute is one which is taken from the environment the shape is in, such as its co-ordinates in a space.

Chronological ranking is the processes of ranking shapes numerically according to the order of addition to a design.

A **colour palette** is a group of colours organised in some way by the designer, **colour scales** and **colour systems** are sets of colours organised with an underlying mathematical form.

A **Designer-Maker** is a particular kind of designer, usually art school educated in a craft based design discipline, works closely with tools and processes used to make artefacts, this may often be shortened to designer or maker in this thesis and refers to the former kind of designer unless otherwise stated.

Design worlds are constructions of objects and relations that designers use to frame design solutions, these range from personal principles to shared philosophies from design communities.

Digital Fabrication is the use of digitally controlled tools, such as laser cutters, CNC milling machines and 3D printers to fabricate objects.

Dynamic is the property of being able to change over time, and is used in the context of shape attributes.

Emergence in a design process is the appearance of an unanticipated phenomena in a design process observed by the designer, may be desirable or undesirable.

3D printing is a digitally controlled additive manufacturing process whereby an object is made by building layers of material on top of one another, by extrusion or sintering. This term

is employed throughout this thesis but is also referred to as additive manufacturing and rapid prototyping in general discussion.

CAD is used as an acronym in this thesis for Computer Aided Design, and is used in reference to software systems used in design for the construction of a digital drawing of a design. The CAD package mostly referred to in this thesis is Rhinoceros or Rhino 3D, a modelling package that is used widely in the jewellery, product, industrial and architectural design industries. Also referred to is Grasshopper, an accompanying visual algorithm editor for Rhino 3D, which can be used to build parametric and generative design tools for producing geometry in Rhino 3D.

Craft is a complex word with many different connotations, in the context of this thesis it refers to the activity of thoughtful making of objects with skilled use of tools and sympathetic use of materials.

A **creative outcome or artefact** is one which is new, useful, valuable and surprising [10]. It is important in the thesis as it is used as a marker of success in design and is often a core aim of the designer-maker. It is assumed in this thesis that creative objects enhance the human experience through enjoyment and or by solving problems in a new, elegant way. In this thesis the point where the designer has the *flash of insight* [10] or *creative leap* [29] to initiate their new design idea is termed a **Creative Episode**.

A **creative mechanism** is a device used to bring about a creative episode, the most well-known is that of use of analogy to reveal new insights.

A **Parametric entity** is one which is open to variable changes yet functionally stays the same.

Tools are understood as artefact which designers use to make specified transformations during the design process on design representations. The term tool is used in an encompassing

way in this thesis, and includes: traditional hand tools, jigs moulds, digital software, digital fabrication tools, sets of sub tools or actions, rules, conventions and guides.

A **Schema** is a model of systems or relationships between objects, used in shape grammar to encapsulate and generalise rule, shape and weight relationships.

A **Strategy** is a planned approach a designer can take to solving a particular design problem.

Shape Grammar is a type of generative design method but can also be used to describe design processes in a more theoretical sense. Shapes are transformed by the application of rules, generating new shapes which can be further subjected to rules. In philosophical terms this process has equivalence with the ways designers may manipulate other constituents of a design process beyond shapes, such as design representations, models, materials and ideas.

Rule in this thesis means a transformational rule, and used in the sense it is in shape grammar, a transformational rule takes an input of some kind, performs and analysis or operation on the it and then gives some kind of modified output.

Variable property 3D printing allows materials with variations in material behaviours, such as flexibility to be printed in one object.

Weights are a way of representing and attributing supplementary material properties to shapes in shape grammar.

2   LITERATURE REVIEW

Design theory and generative design, craft and creativity span somewhat diverse academic spheres each with their own literatures. This section brings together a literature review of each of these.

Section 2.1 of this literature review deals with craft literature, taken by this thesis to be synonymous with making in design. Much of the literature around craft is in the tradition of art history academia, describing the work of artists, designers and artisans and their associated ideas and place in a historical and political narrative. A brief look at this area has been undertaken, however is not particularly helpful in addressing the aims of this thesis. A viewpoint from philosophical and anthropological writing on craft, tools and making has influenced some of the thinking throughout this thesis and literature from these areas is also included in this section.

The next section, 2.2, looks at relevant design theory literature. Design theory research is a relatively new field of research, the leading journal on the subject, Design Studies, was launched in 1979. Design research mostly focuses on the cognitive aspects of the activity of designing, and predominantly looks at cognitive reasoning through verbalisation, sketching and communication, mostly in the fields of architecture, industrial and design engineering. Design-through-making processes are severely under investigated and underrepresented in this academic community. Ideas from this community do have consequence to this thesis and the methodological approach of such research does tend to be more rigorous and academic, with recognised methodology taken form the social sciences, something lacking in much discourse on craft and making, so a selection of relevant papers is examined.

Section 2.3 looks at a strand of design research, shape grammar, which is covered in some detail in this literature review as it is one of the main focusses of this thesis. Shape grammar is a method for designing and also a method to describe designing through rules and

transformations. Also a review of wider research on generative design and use of computer systems in design fits into this section.

Following this section 2.4 of the literature review examines creativity in a general context and then more specifically in design theory literature. For the purposes of this thesis a design process containing creative episodes is considered to be a successful one, therefore understanding how creative episodes occur is important to the thesis as it is used as way of analysing and improving designer-maker activities. Particular focus here is on literature that formalises creativity as a rule based process, to try and find useful connections to answer the research questions.

Section 2.5 summarises some recent thinking on the arrival of digital design tools in architecture and other disciplines from design theory, to establish the way these are perceived by design researchers. Finally, section 2.6 returns to the subject of craft, but looking at the current research and zeitgeist concerning design, making, craft and digital tools which has come to the fore since this research has begun. Section 2.7 present the research questions that arose from this literature review.

2.1   Craft

There are many complex ideas and connotations associated with the word 'craft' in the general domain, stemming from how it has been appropriated in different contexts from the epistemological, the theoretical to even the political [45], as Paul Greenhalgh remarks, the word has '*no stable significance*'[45, P20]. This section reviews literature that has explored the relationship between craft and design and also literature that has theorised on the pragmatics of making objects.

2.1.1   The role of craft in design: a brief history

The role of the 'crafts' in society has been debated since the industrial revolution, when the machine usurped the role of the craftsman in society [45]. Craft did continue to play a pivotal role in design throughout the Arts and Crafts movement, at the end of the 19th century John Ruskin inspired the Arts and Crafts movement, which championed craft, calling for a return to artisan production in the face of 'dehumanising' industrial manufacture [23]. The movement may have been ideologically noble, but in reality William Morris produced fashionable wares for the middle classes and neither embraced nor impeded industrialisation and all its potential [23].

Following this Walter Gropius founded the Bauhaus, embracing the potential of industrial production, and so craft began its supporting role to design. Despite this in the Bauhaus foundation course the students were expected to undertake three year craft apprenticeships, this knowledge brought '*clarity of expression….in order to give conviction to their ideas*' [31]

Craft and making continued to play a role in design, in the work of the designer-craftsmen of the 1950s, right up to the current craft sensibilities of many contemporary designers [2]. However, Modernism valued clarity of form, function and the machined aesthetic, seemly making craft an anachronism practically and intellectually.

Craft fared no better in Post-Modernism, where concept was everything and materiality and making were side-lined, and work exhibiting any personal making skill became deeply unfashionable [96]. Despite this, personally making objects did play a crucial if quiet role in the work of many canonised designers over these periods, Charles and Ray Eames made their own prototypes from new fiberglass composites, such as 'La Chaise' shown in Figure 2-1, and developed their prototypes in the workshop in a hands-on, iterative manner [32]. Other notable designers through the post war years such as Georg Jenson, David Mellor and many others all served craft apprenticeships before becoming designers [23].
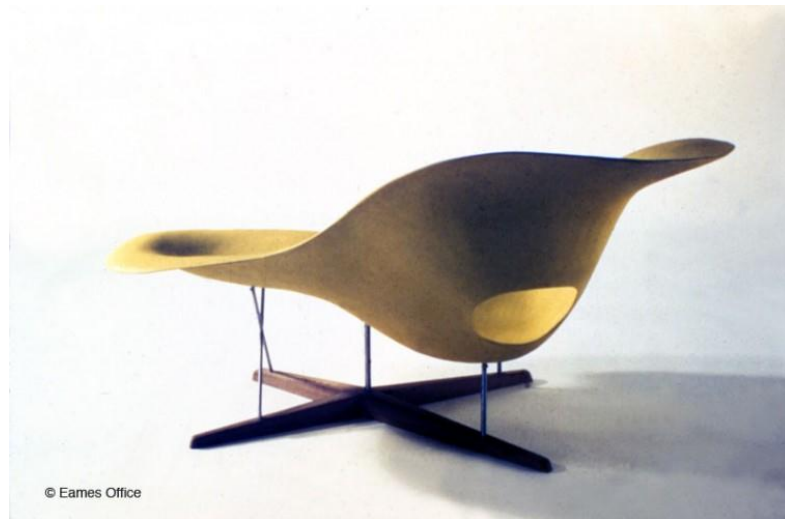
Figure 2-1: 'La Chaise', fiberglass seat, by Charles & Ray Eames, 1948

Moving into post modernism materiality and craft seemed even more diminished in an age where the most important aspect of design was imbued meaning and concepts [2]. Despite this designers like Ron Arad and Tom Dixon were using metalwork techniques to make one off pieces in the 1980s, such as Arad's Rover chair, Figure 2-2.

Figure 2-2: Rover Chair, Ron Arad,1981

From the 90s onwards, Droog, a consortium of European designers, epitomised postmodern design by producing quirky, novel products, and are considered to be leaders in the design world [2]. Droog designers often referenced handcraft in their work, such as in Damekersvan's lace fence, Figure 2-3, to produce idiosyncratic objects, which often made use of visual puns and ironies.
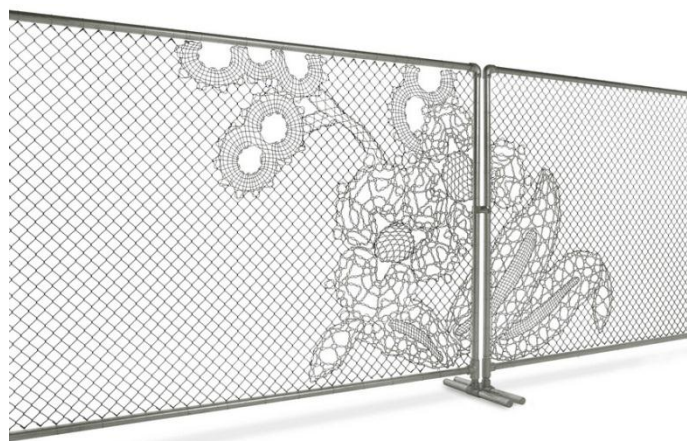
Figure 2-3: Lace Fence, Demakersvan for Droog, 2005

At a talk given at the Royal College of Art InnovationRCA evening in 2009, Jonathon Ive, head designer at apple revealed and emphasised that physical prototypes rather than CAD software dominated his design process. He explained that Apple designers went to Japan to learn ancient aluminium smithing techniques to inform the designs for the casings of the products

[51]. This demonstrates that even the contemporary and exceptionally successful digital products produced by Apple find form through making.

In present times a renaissance of the value of craft and making has happened, this is discussed in more detail in the final section of the literature review, 2.6.

2.1.2   The principles of craft

Glen Adamson is one of the few authors writing on contemporary craft. His approach is in the tradition of historical and critical art academia rather than analysis of the practicalities of the way craftspeople work. Adamson's book *Thinking Through Craft* examines craft in such a scholarly context but it does provide a useful definition of craft: '*a way of doing things….an amalgamation of interrelated core principles*'[2]. He defines these principles as: that craft is supplemental to art and design, is entrenched in material experience and is skilled. Using the word 'supplemental' is perhaps doing craft a disservice in some design contexts, however the second and third principles provide suitable points to explore further in the next sections.

2.1.3   Working with materials

As Adamson states craft is '*entrenched in material experience*' [2], indeed in '*the crafts*' as disciplines are actually defined by materials; ceramics, metalwork, woodwork. Applied artist and writer Caroline Broadhead describes craft as an '*exchange*' with materials [13].

Tim Ingold, from an anthropological standpoint on making, argues against the idea of hylomorphism, a theory developed by Aristotle and embedded in Western thinking [49,50], whereby we seek to impose static forms upon matter. Ingold rejects this idea in favour of a more dynamic explanation of making, where the matter is constantly changing and informing the shapes it takes, the maker works with this material flux, this formation process is given the primary importance by Ingold, rather than what we consider a finished object. Using the analogy of meshwork, in opposition to networks, he brings forward the idea of '*creative entanglements*', things made of flowing interwoven threads with points of connection to

produce new entities. He points out that no object is really a static form as we often perceive, particularly when it comes to the perception of a designed object as '*finished things*', actually things are made, grown and erode over time. This is a critique of much of the modernist thinking around design, a rejection of '*form follows function*', and the idea that the designer can make a drawing that is exacting of the actual thing that is exists. Through seminars and teaching he has come to the conclusion that to truly understand and produce something worthwhile one has to do and experience working with materials for one's self.

Writer on craft Pye [89], says of material, '*We talk as if good material were found and not made*', reminding us that most physical materials ready to be worked by a maker have already been through many refinement processes. He states that materials have '*properties*' these are both the scientific physical potential, such as flexibility and the qualities culturally projected onto materials, such as value or personified characteristics; such as the contemporary western perception of the honesty of wood.

Pye [89] also states that despite the perception that most craft work is done by hand almost all material must be worked by way of tools. Tools are usually specified to particular materials, McCullough defines a medium as a '*class of tools and raw material*' [77], and so the next section looks at literature on tools.

2.1.4   Making with tools

Pye seeks to define the nature of making, or '*workmanship*' by determining how tools are used. He describes the '*workmanship of risk*', and associates this with craft, where the end result is down to the skill and dexterity of the maker as the tools are controlled closely by him or her, most likely by some relation to bodily movements, with potential for errors. The '*workmanship of certainty*' is where the end result is predetermined and standardised by machines or tools or '*jigs*', as found in industrial settings, with the potential for errors reduced. Pye sees this as a spectrum, and the implication is that a high level of individual control over the making process

is a feature of craft work. Pye suggests the main desirable feature of the objects produced by the '*workmanship of risk*' is '*diversity*'. This is an aesthetic value similar to that found in nature – subtle variations within a framework such as wood grain, which add a pleasing richness to forms and surfaces. In opposition smooth surfaces and straight lines, the outcome of using '*jigs*' are also an aesthetic that many find desirable as demonstrated by the popularity of products such as Apple iPhones. No matter which of these surface aesthetics is superior, this idea is perhaps obsolete with the advent of more complex digital software and fabrication which could produce a higher level of detail in production processes than when this book was written.

Dormer contributed to and edited the book *The Culture of Craft: Status and Future* [28], in which he writes a chapter on craft and technology. In some ways the content is out of date as technology and its uses by designers and makers has moved on dramatically, however Dormer does provide key insights by building on some of Pye's idea about the control of tools, suggesting that the difference between craft versus design is a question of '*personal knowhow*' versus '*distributed knowledge*'. In a craft process the maker has close control over the fabrication process, rather than being detached as the case may be for some designers, this moves the emphasis onto the idea of control as knowledge expertise and decision making rather than the dexterity of hand. As he explains: '*Designers lose control of their creation once they relinquish it to production, where as one of the strengths of handicraft-based art form is the flexibility it allows for the artist to change, expand and explore his original intention or design.*'[28, P30]

This description of design and designers '*losing control*' of objects is a simplification, fabricators may interpret representations with some tacit knowledge, yet designs are explicit representations, the point of which is to give the designer control of the end product. What may be relevant here is the idea that the designer-maker, working directly with the tools of production can take a more exploratory approach to design development in terms of this part

of the design process with the physical object rather than the representation, more contact with tools may give rise to more unusual objects being designed with those tools.

Dormer's main concern about technology was that, for instance, if all designers are using the same software and means of production, objects begin to take on a ubiquitous aesthetic aura, something demonstrated by the popular criticism currently levelled at car design. Again Dormer wrote this in a time when digital technology available to designer-makers was more limited, but using standardised tools, of any kind, analogue or digital, under greater or lesser control, is likely to produce outcomes with similarities. Despite being a contemplation of technology, this leads to indication that a designer seeking to design something new, and be creative in their designer may want to question the use of standardised tools used in common ways in their industry.

The main advantage Dormer draws out from talking to designer-makers who were using new technologies at the time is that labour saving aspects and reduction of risk provided by technology, such as in the use of a programmable, automated loom for example, allowed the makers to experiment and be inclined to take risks without fear of losing hours of valuable time on a piece of work that was unsuccessful.

From the two main rhetoricians of craft in the last century, Dormer and Pye, we can draw the relevant ideas that making is about having close control and knowledge about how something is made, which can offer the advantage of seeing different possibilities that designers who are fragmented from manufacturing processes may lose out on, whatever the different aesthetic implications may be.

2.1.5   Skill and expertise

Skill is the last of Adamson's core principles of craft [2]. A study of skill in making is the essay *The Art of the Maker: Skill and Its Meaning in Art, Craft and Design* by craft writer and critic Peter Dormer [27]. Motivated to critique the diminishing contribution of craft skills in postmodern

art, he investigated the process of becoming skilled by attempting to learn head modelling in clay and calligraphy. He discovered that such practical skills were acquired through learning and following rules associated with the particular craft, practiced until they became intuitive, where effective making actions and decisions become instinctual rather than deliberated. Also a deeper understanding of quality or connoisseurship was achieved in the objects. The idea of making practices following *'rules, conventions and patterns'* fits well with ideas in creativity and shape grammar, important aspects of this thesis and discussed in following sections.

This idea that by physically doing processes they eventually become intuitive is described by McCullough: "*Instead of thinking the actions, you feel the actions….As an expert you sense what to try when; how far a medium can be pushed; when to check up on a process; which tool to use for what job*" [77, P27].

Ingold [50] talks of '*anticipatory foresight*' in making, where the maker, exemplifying a cook or a gardener has some idea where things are going, experience tells them what to expect, and how to produce or '*hunt*' a particular material manifestation of their materials.

Like the concept of skill occurring in craft literature, expertise has been of interest to design researchers, finding out how and why experienced designers are successful is using knowledge.

Cross [21] has explored the meaning of expertise in design by gathering an overview of various studies. Generally it would seem that experts in design are able to move more quickly between different design activities and consider more aspects of the process simultaneously, they understand and envisage the interrelated and multiple effects of changes on an aspect of a design better than novice designers.

From Dormer's investigations we can accept that as designer-makers accumulate rule-based knowledge of making processes they can start to work more intuitively and produce higher quality works with greater ease. This seems to concur with Cross's findings that the expert designer better understands the propagation of changes made on a design throughout different

levels of abstraction. From the point of view of Dormer this skill is accumulated through exercising conventions until the time comes the maker can begin to challenge and change these to make their own rules to suit their aims. In terms of tools and materials and designer-maker practice this implies that a depth of knowledge and experience offers more potential for discovering new ways to use tools and materials and understanding the effects these may have.

2.2 Design – the new academe

Nigel Cross's editorial in Design Studies [22], *Forty Years of Design Methods*, gives a comprehensive overview of the history of the area of research. Design Methods as a field of research began in the 1960s with the first conference on the subject and associated publications. Initially the goal of the community was to find, as Herbert Simon [101] put it, a '*science of design*', to rationalise and bring logic to the process of design, but as early as the seventies key players began to question if trying to characterise design as a science was an overly reductive way of analysing a process that incorporates complex cognitive problem solving [22]. The field was reinvigorated by Horst Rittel's idea that these methods could be built on with new, more detailed generations [22]. Research went on in the fields of architecture, industrial and engineering design and by the 1980s the emphasis was on the idea of design cognition, and the widely used term '*design thinking*' [22]; design as an intellectual problem solving process to find a satisfactory solution to a problem. It became accepted that the design process was not a science in itself, as the first design methods research attempted to characterise it, but could be studied with scientific style methods, a systematic approach to try and learn more about design and designers [20]. Cross states that design methods research came of age in the 1980's and since then a proliferation of journals and conferences have come into being, creating a wealth of literature on the subject [22].

2.2.1 Designing with materials

Design methods research has been primarily focussed on the architect, the industrial designer or engineer, these are designers that are usually removed from the production and making processes, handing over plans of some description to builders and manufacturers to make the actual objects, and also usually trying to satisfy a fairly specific problem or brief. Obviously some knowledge of production processes is required, but it is safe to assume that the subjects of much design methods research are not directly experimenting with materials directly as a designer-maker may do.

In the 1980s Schön introduced the idea of design, and other disciplines with practical aspects, as being an intuitive, often tacit [93], process, where practitioners respond to complex and unique problems [95] according to their experience. This can be interpreted as the designer-maker responding in the moment to the tools and materials they are using to design, with reference to other aspects that may concern them, this process is echoed in the ideas of Ingold [50] and Dormer [27].

Schön suggests that designers create '*design worlds*' – sets of personal and shared objects, constructs and relations, in which they have '*design transactions*' where actions and results guide the design process, acted on the '*materials of a design situation*' [93]. We can assume that his use of the word 'materials' includes actual physical materials, but seems mainly to refer to more abstract idea of any related entity deemed relevant and goes on to mostly analyse the nature of paper based sketching design processes in his research.

Schön and Wiggins [94] analysed architecture students using the medium of sketching with pen and tracing paper to investigate the idea of '*reflective conversations*'. They found that the subject goes through an iterative process; repeating the steps of '*see – move – see*' as they draw and redraw their initial ideas for a building. The designer looks at the latest sketch, performs an action or alteration upon it and then evaluates the result in terms of their goals. It could be said that a maker is likely to undertake similar steps; a judgment, followed by

action/manipulation of a physical material mediated by tools, followed by a similar assessment of the result which informs the next action. Although both rely on small iterative actions to stimulate and guide a path forward, there may be many similarities. Sketching used in this way is conceptual and relatively unconstrained medium, similar actions with a material or process are perhaps more defined by the nature of the material.

Darke [25] presented the idea of the '*primary generator*' in design. This entails the imposition of objectives, singular or a set which the designer self imposes as a method of initially generating ideas for the design. It was found from interviews that the architects defined objectives drawn from their personal beliefs about how architecture should be done – such as being sympathetic to the surroundings and how buildings should be built, and used these as a spring board for their initial ideas. The conclusion drawn was that for the most part the architects interviewed used these objectives as part of a design method of '*generator-conjecture-analysis*', as proposed by Hillier, Musgrove and O'Sullivan [47] in their design process rather than the analysis-synthesis model developed in design theory in the 1960s. The implication is that designers work differently in different fields – those in industrial design and engineering tend to use synthesis-analysis and those in less constrained situations tend to use the generator-conjecture-analysis approach.

These are central and accepted theories within the design theory community, and although based in sketching they do appear to have much credence for designer-makers. It seems likely that for designer-makers tools and materials are key parts of design worlds, and that the '*reflective conversations*' they have in the design process are with tools and materials. It also seems possible that the designer-maker's '*primary generators*' are often the tools and materials they work with and the process of '*generator-conjecture-analysis*' is aligned with the kind of experimentation and material sampling regularly carried out by designer makers. This thesis seeks to confirm these specifics, which are not articulated by the above authors, as these examples are focussed on the manipulation of design representations, such a sketching, rather than actual objects designed and made directly with tools and materials.

George Stiny [104,105,106,107,108,109] and others have developed the theory of shape

grammar over a number of years. The generative mechanism in shape grammars are

transformative rules concerning shapes and their spatial relationships which are formalised to

describe and generate geometric and topological patterns and structures. Shape rules are

represented and used visually, transforming shapes into new shapes, as shown in Figure 2-4. A

shape or a sub-shape in a set of shapes is matched to the shape on the left hand side of the

rule, where upon it is replaced by the shape(s) in the right hand side of the rule.
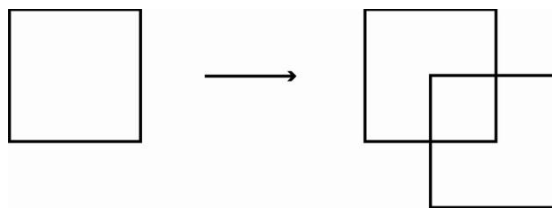
Figure 2-4: Example of a shape grammar rule

One of the most significant phenomena of shape grammar is the appearance of emergent

shapes as rules are applied. An example of this can be seen in Figure 2-5, the first resulting

shape can be seen in several different ways, as two squares overlapping, or as two L-shapes,

there is also a smaller third square to be found in the overlap. Figure 2-5 shows the

reapplication of the rule shown on the smaller emergent squares, as these are the same shape

the rule can also be applied to them if desired. Emergent shapes can then be used in further

rules however the designer sees fit. Stiny says of the ambiguity found in the perception of

emergent shapes: '*The novelty it brings makes creative design possible*' [109]. Shape grammar

characterises of creativity in a similar way to other creativity and design research, that

exploring sets of rules can reveal new and useful designs.
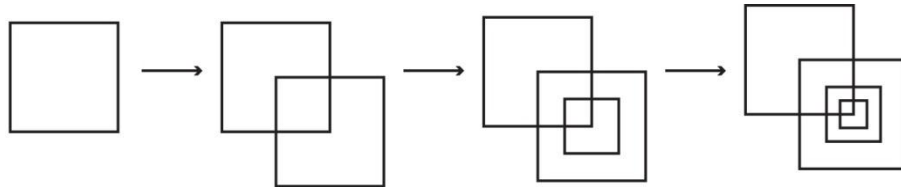
Figure 2-5: Example of reapplication of shape grammar rule on emergent shapes

Shape grammars, have been widely explored in design theory academia, building on the groundwork Stiny has laid out in previous years. The following sections look more deeply into certain aspects of shape grammars and the work others have done that is of interest for this thesis.

2.3.1   Shape grammar operations

Stiny [108] formalises shapes through four basic elements; points, lines, planes and solids. Within any shape an infinite number of the elements can be embedded, and picked out visually by the designer for the application of rules.

The elements adhere to Boolean algebras: sum, product and difference, and these are performed on the maximal elements of a shape, this is shown in Figure 2-6.
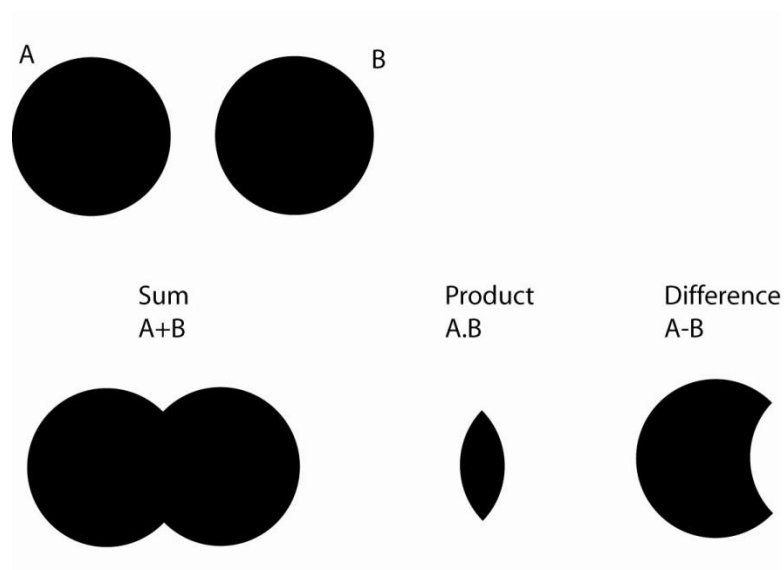
Figure 2-6: Boolean Operations of Shapes

Informally maximal elements are shapes that are discrete from one another, but contain infinitesimal numbers of connected basic elements. For example, Shapes A and B are maximal elements in Figure 2-6, but these can contain an infinite number of smaller black shapes of the designer's choosing.

Using additional elements in shape calculations, such as points, which mark out specific spatial features or sub-shapes, can help control where shape grammar rules are applied by providing reference points, removing undesired ambiguity when using similar or symmetrical shapes that have several ways a rule could be applied [108], as in Figure 2-7. The first rule has no reference points so, as the figure shows, it can be applied at different places, giving different new shapes and many more possibilities, the second rule contains a point to guide where the rule can be applied, only on squares with a reference point, the careful positioning of this point means that the resulting shapes will only produce straight rows of consecutive shapes. This concept has similarities to Pye's ideas on workmanship and jigs [89], without a reference point there is more variety and risk about the outputs from the rules, particularly if it is applied many times, but also the chance of something unexpected, which may be useful.
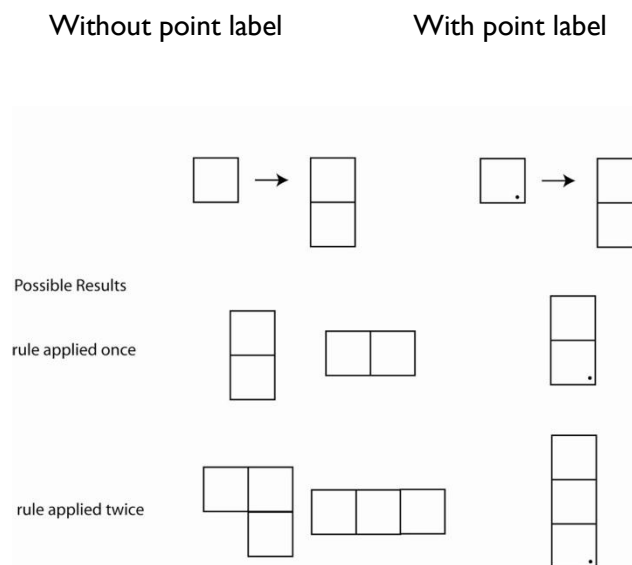
Figure 2-7: Example of using points to define specific relations

The basic operations of shape grammar seem to have much commonality with making. Both are concerned with visual perception and carrying out informed transformations on an object. A piece of material worked on by a designer-maker could be considered equivalent to a three dimensional shape in a shape grammar, with the capacity for transformation. It follows that shape grammar may be useful for explaining and carrying out design through making processes.

2.3.2 Schemas in shape grammar

Later work by Stiny also proposes a system of rule schemas which can be used to generally define types of rules [109] which can then be universally applied to shapes. This represents a move by Stiny in later work that describes the underlying principles design processes rather than producing specific applied shape based generative design systems. The rules in schemas relate to branches of mathematics and are notated as operators for a given shape, x.

Stiny's schemas take forms such as:

$$x \rightarrow prt(x)$$

is an operation which isolates a part of shape x for use in further rules and performs in the manner of Boolean algebras.

$$x \rightarrow t(x)$$

is an operation that transforms shape x into a different shape and is with reference to geometric changes.

$$x \rightarrow b(x)$$

is an operation that isolates the boundary of shape x for use in further rules and relates to shape topologies. Stiny presents a range of schemas, further variation on the ones mentioned here, all of which are discussed in detail in the context of making in section 7.1.

Stiny demonstrates various moves artists and designers might make in terms of '*calculations*' with these operations, by applying recursion, nesting and inverting to parts of a design. He then goes on to discuss how the concepts of recognising, embedding and transforming entities more generally are the basis of creativity design activity, as the schemas represent, and therefore it would seem that schemas may allow the designer a freer and more fruitful approach for the application of the principles of shape grammars than strict geometric rules.

Woodbury [113] and Li [68] propose another way to use schemas in shape grammar: replacing shapes in rules with shape schemas on both sides of the rules. Shape schemas rules can target shape instances defined by a set of constraints, performing operations on these to produce new, altered shape schema. This makes their application more flexible but the behaviour more complex in comparison to Euclidian shape grammars, particularly in recursion. Defining and identifying shape instances for recursive generative designs becomes a complex computational problem, one that Li and Woodbury have begun to tackle but still requires further work.

2.3.3   Labels and weights

Shapes can also be labelled to classify them into separate classes or sets [108]. This means that elements labelled differently do not interact with one another, they are effectively on different '*layers*', Stiny's [108] analogy from CAD programs. Elements with different labels will not interact with one another or become embedded in one another in the result of operations where they may overlap.

Stiny extends the idea of labelling with weights; shapes and associated weights can be considered together in rules and weights can represent properties such as line thickness and colour. Unlike labels, shapes with different weights can interact, therefore definitions for calculating resulting weights from interactions are required.

Stiny proposes algebras of weights follow the rules of Boolean algebra for sets. The weight of the emergent shape in a **sum** of two overlapping shapes is the maximum of the combined weights: so for weights **u** and **v**, **u+v** = **max{u,v}**. For the **difference** between two overlapping shapes, is the product or the minimum of both so for weights **u** and **v**, **u.v = min{u,v}**. These definitions can be extended for general weights or properties associated with shapes which have a lattice structure where greatest lower bounds replace minima and least upper bounds replace maxima. Stiny presents a simplified overview of the idea in the book *Shape* [108] and more comprehensive, mathematically notated, definition in an earlier paper [106].

Previous to Stiny's weight definitions, Knight presented the idea of colour grammars [59], she set out to formalise the interactions of two dimensional shapes of different colours, or 'colour fields'. She suggests some logical systems for artists and designers to use to calculate the colour of overlapping colour fields, in other words shape intersections, using grammatical operations. Falling into two categories, the first is to let the colour of the most recently added shape to dominate the others, as if the designer or artist is chronologically adding opaque colour in layers or introduce a ranking system so that certain prescribed colours dominate other prescribed colours. The second approach is to mimic transparency in some way, by giving overlapping areas a tertiary colour of the designer's choosing. She suggests that any subtractions or difference by leaving the shape area as a blank space, most likely as this simplifies the calculations and also mimics the action of erasing colour from a drawing or painting.

Knight builds on this colour grammar system in a later paper [61] supplementing the grammar of a form of traditional Persian garden where squares are recursively divided into further squares to create symmetrical garden designs segmented with borders and canals. Knight adds colour to the sections created by the recursive rules to signify different kinds of planting or canals in the designs and investigates the use of ranking and parameterisation in more depth.

Weights perhaps can be used as a link between shape grammar and the world of materials. However, the idea of having a shape onto which you apply a material property is very much at odds with much of the literature on making previously discussed in this literature review, particularly the ideas of Ingold [50], where materials in flux influence the structures they take. Shape Grammar weights as they stand do not affect the geometry or spatial relations of the shape, they are calculated separately from the shape calculations. Both Stiny [106] and Knight [60] mention that weights could be parameterised, Knight suggesting these could be related to variables related to the shapes. This is perhaps the wrong way round from physical making practices – where material properties define the shapes.

2.3.4   Shape grammar applied in design processes

Since their conception shape grammars have been used in several ways, one is as an actual design tool, using shape grammar rules as a mechanism for generating new designs.

In early research Stiny [104] and Stiny and Mitchell [105], defined classic designs with sets of shape grammar rules and demonstrated how these could be used to generate further versions. Koning and Eizenberg [66] followed suit with the '*language*' of Frank Lloyd Wright's prairie houses, they claimed shape grammar helped them better understand the composition of Lloyd Wright's designs and led to successfully generating new versions of the style. Since these early investigations using shape grammar rules as a way to define and generate designs become an established method in the design research community, these include the following key contributions.

Cagan et al. [75, 76, 88] have researched the potential of using shape grammar to define a brand styles; creating rules that if adhered to should generate new designs in keeping with a brand. One of the papers uses Harley Davison styles; previous designs are analysed in 2D projections and a number of rules are proposed, these were then used to generate new designs in 2D projection. These new designs were offered for evaluation by online survey and

were successfully identified as having the Harley Davison brand identity. Prats et al. [87] also come to similar conclusions, that shape grammars can be useful tools for product designers to explore styles.

Knight suggested that grammars can be exhausted and so a need to develop new design languages exists [55, 56, 57, 58]. She suggests new languages can be inferred by making modifications to rules in an existing grammar by changing the shapes and the spatial relations in a rule. Demonstrating this idea she shows how a design language can be defined as a simplified 'normal grammar' a grammar comprised of spatial relations and non-spatial relations (such as the order rules are applied in a design generation, modelled as 'state labels') this in turn allows changes to be made easily and produce new design languages. She demonstrates this with an extension of Frank Lloyd Wright's Prairie House grammar [58].

In papers by Ahmad and Chase [3] and Khan and Chase [54] it is proposed that style change in families of designs could be achieved by modifying grammars by adding, subtracting or modifying the rules of a style grammar according to adjectival descriptors augmented onto the rules that described their aesthetic qualities. This was shown to aid designers in experiments trying to generate new designs according to style goals.

Chase and Liew [17, 18] also extended Knight's work on rule modifications to include the modification of the functional, behavioural or structural descriptions of designs. Function-Behaviour-Shape descriptions for a design are represented as graphs, showing relationships between these properties. In order to redesign, the FBS descriptions of existing designs are modified according to the additional requirements, the designer's knowledge base provides the appropriate modifications, and so new designs can be produced with the new FBS descriptions.

Shea [98] et al. explored the role of shape grammars in engineering, developing a grammar to explore the possibilities of designing truss systems. She combines the shape rules which act as a topological generator with a stochastic search to optimise the structures for various traits, even an aesthetic value based on the golden ratio. As part of this optimisation Shea develops

the idea of design '*syntax*' – hard constraints and '*semantics*' – soft constraints in an engineering design scenario.

Shea [99] also implemented a three-dimensional shape grammar for an aperiodic tiling system, creating a design tool. This tool generates an aperiodic three dimensional tilling, which have been discovered recently in mathematics and in nature – in quasicrystals. The tiling can be subdivided infinitely with similar tiles to create hierarchical, nested structures. Shea proposes such a tool has potential for use for architectural spaces, structures and facades. This research is relevant here as it takes its grammar from a mathematical/natural phenomenon and translates it into an applicable design tool.

Much of the research carried out around shape grammars has been into the implementation of basic shape grammar computational systems for possible use by designers. Several systems in have been created, such as Shaper2D [78], an implementation to deal with curves by Jowers & Earl [53] and and an automatic generator for the fabrication of designs by Wang & Duarte [112]. All these grapple in various ways one of the main difficulties of implementing shape grammars: shape recognition and dealing with the ambiguities found in this process; classifying shapes computationally is very difficult. McCormack and Cagan [75] tackle this problem by devising a parametric, hierarchical system of shape detection.

Some research has been carried out on shape grammars in conjunction with digital fabrication. Sass [92] has been investigating digital fabrication in architecture in conjunction with shape grammars. He set out a 'wood frame grammar', which translates a three dimensional model house into parts ready for two dimensional CNC milling. The result is a way to efficiently manufacture parts for design, using the affordances and constraints of a manufacturing system. The project involved a very large number of rules to achieve the desired result, a grammar for the design of the house and then a grammar for its construction which creates the parts for manufacture. The conceptual idea was that prototypes of buildings could be produced very

quickly allowing the architect to test out different ideas and find any problems early on in a building project.

Computational shape grammar design systems are difficult to implement unless they are very specific, due to the difficulties in dealing with the ambiguities of shape recognition. The most significant work in these studies is spent defining and implementing the rules; once this is done multiple versions of a design can be produced, however these will be closely related to one another. Applications of shape grammar weights systems for 3D printing have to date not been researched.

2.4   Creativity

A general overview of creativity is presented in the work of Margaret Boden, who has written extensively about creativity in science and the arts and the potential for creativity in artificial intelligence [10]. Her definition of a creative idea or artefact is one which is '*new, surprising and valuable*'. She also makes a distinction between what she terms psychological '*P-creativity*', a creative idea new to the author and historical '*H-creativity*', where the idea has never before had by anyone in history.

Csikszentmihalyi [24] interviewed nearly a hundred creative people from different fields, interviewing them to find patterns in the lives and work of creative people. He acknowledges the complex subjectivity of how people become and are deemed to be the sole originators of certain phenomena or ideas, which Boden [10] seems to gloss over in her description of '*H-creativity*'. He describes the '*traditional*' five steps of the creative process: the first is a period of immersion in a set of issues, this is followed by an incubation period, much of which occurs in the subconscious and then the third step of the '*Aha! Moment*', when a solution falls into place. This is followed by an evaluation of the idea and then an elaboration to complete the work. This process happens iteratively on a lesser and greater scale throughout the creative process,

with fresh insights occurring throughout, these hopefully build into a substantial and influential body of work which can then be recognised a creative.

2.4.1   Rules in creativity

Csikszentmihalyi's [24] definition of creativity is '*..when a person, using the symbols of a given domain such as music, engineering, business, or mathematics, has a new idea or sees a new pattern..*'

Boden [10] similarly uses the idea of manipulating symbolic conventions to define creative ideas, her background is in cognitive and computer science so her definitions are particularly logical and have a computational slant. She suggests three types of creative activities, each deemed more creative than the last.

The first is '*exploring conceptual spaces*'; searching within predefined sets of rules for new assemblies within a defined genre. Boden considers this search as taking place in the mind, describing it as a metaphorical map of terrain to be explored, but also gives examples of artificial intelligence systems performing this search. She cites examples of widely known conceptual spaces as haiku poetry or jazz music, where certain rules are followed to create works. The rules can range from the invented, the number of words in a sentence in haiku for example, but also imposed by physics – the properties of physical phenomena, such as sound waves in music.

Dormer [27] states that craft activity '*follows rules, conventions and patterns*', some come from the physicality of the tools and materials, others from styles and traditions. Boden doesn't acknowledge that a material space could be searched in a similar way, but it seems that this is what much of design-through-making is, searching material and tools for new designs. This definition also corresponds well with shape grammars, which can describe a design through shape rules, such as the style rules of Frank Lloyd Wright's Prairie houses [66] which can then be used to generate a range of designs within these rules.

The second form of creativity Boden defines is called '*transforming the space*'. This occurs when accepted sets of rules are modified in a new way. This can happen when rules are bent or broken in a surprising way and still produce a new and useful outcome. Dormer gives an example from the craft realm that resembles this kind of transformation of rules, when he studies the work of an expert calligrapher he observes that the expert breaks some of the rules of script writing to achieve artistic emphasis in the pieces [27]. This also has similarities to Knight's [55] suggestion that rules in a grammar can be modified to produce new design languages. The third kind of creativity, the rarest, is the extreme end of this spectrum, where whole new conceptual spaces are created in their own right, transformed so categorically they constitute a new genre of music or art, for example.

Some transformations take place by bringing in rules from another conceptual space to use in conjunction with the original set to create a new space and so new works. Boden describes this happening through analogies, concepts with partial similarities which can then reveal or add new concepts to the other.

In *The Craftsman*, a pop-sociology book with a narrative tone, the writer Sennett [96] offers some interesting ideas in a craft framework from anecdotal evidence. He suggests that tools and techniques can be transferred between media. The example cited is that weaving techniques were distilled into woodworking as mortise and tendon joints in ancient Greece. He claims that practical skills and knowledge in craft practice allow intuitive leaps between techniques and materials and techniques are reformatted to reveal new possibilities in their unsuitability. This idea concurs with Boden [10] on the importance of analogies to stimulate creative ideas, but with a specific example relating to a way this can happen with tools and materials.

For the independent designer-maker design creativity is likely to be a core aim in their practice, to find new and useful ideas to advance their careers in their chosen domains by producing more valuable and original objects. This literature, particularly Boden's definitions of

types of creativity that come from a computational perspective, are useful for helping to categorise tool centred creative episodes in making, in turn a set of formal strategies can be established to guide the designer-maker towards improving design creativity.

2.4.2   Design creativity

Creativity is discussed widely in design academia, researchers have tried to find out what strategies designers use to be creative in solving design problems.

In a study on design creativity in early ideation using sketches and models, Acuna and Sosa [1] define design creativity as the ability '*to generate concept proposals that are judged by experts as original solutions that respond in novel ways to a clear set of requirements*', focussing the definition in the ideation and generation phase of design processes. In the study designers using modelling in the ideation phase came up with solutions that were rated slightly less original but slightly more functional than the group using sketching. This infers that working directly with materials imposed tighter but more realistic restrictions on the design outcomes than sketching.

Design theorists have offered and tested approaches for designers to stimulate creative ideas by encouraging different ways of forming analogies and brainstorming [19]. Goldschmidt and Tatsa [43] studied architecture students to correlate the quantity, nature and creativity of ideas a student had in response to a brief and the success of the resulting designs. It was found that generally the quantity of potential solutions generated had a positive effect on the students' creativity and in turn appraisal of their work by tutors. However, it also appeared to be important for the students to home in on a favourable idea and then concentrate on developing it 'vertically' (in more detail) rather than hopping laterally (to a slightly different idea), echoing the findings of Cross's [21] study of expert designers, who concentrated on sharpening a specific idea rather than making conceptual shifts. Suwa [110] found that creative interpretations came through designers using a cognitive skill he named 'constructive

perception', where the designer must be aware of their personal perception of the design problem in order to generate novel solutions.

Dorst and Cross [29] report that the design process is a matter of co-evolving both the problem and the solution spaces; clarifying the affordances and constraints of the situation and letting these inform the solution and vice versa. Dorst and Cross describe creativity as finding the suitable '*bridge*' between problem and solution space; a creative leap where the designer suddenly becomes enlightened by an unexpected new piece of information in the design problem.

Similarly Rivka Oxman [84] highlights that one of the key parts of Schön and Wiggins' '*see – move – see*' protocol is the appearance of emergent properties the designer can make use of to help solve the problem. A crucial aspect of making use of serendipitous emergent properties is a requirement of the user to anticipate and, critically, to recognise their presence [84]. Such emergent properties are often the key to a creative idea in the design process.

Eckert and Stacey have researched creativity in design situations, particularly in the knitwear industry. One paper [103] presents the findings that design problems range from being under constrained, such as in fashion design, to over constrained, in engineering. In these situations it has been seen that the designers find it easier to find creative solutions by adding constraints in under-constrained situations and temporarily relaxing constraints in over-constrained situations. It was also found that many designers find that constraints, particularly hard constraints force creativity as prior solutions are rendered unsuitable and they have no choice but to innovate [102]. Eckert and Stacey have also found that creative thinking is enhanced by the designer having a rich pool of stimulating resources and opportunity for communication with other designers [33].

Gero [41], coming from an engineering design view point has tried to model emergence to make a computational framework of '*creative design*'. Gero describes creativity in design as a new, unexpected and valuable result brought to being by the combining of two schemas, the

second then showing previously hidden similarities, or emergent features. When combing schemas *homogenous* variables are added or *heterogeneous* variables are substituted into the new schema. Gero states three mechanisms through which variables can be added –*analogy, mutation* and *emergence* and presents an evolutionary process model for computational design using shape grammars and their emergent properties as an example. Again creativity is linked to the use and exploration of rules by Gero, by formalising creative incidences in design with computational formula and suggesting similar mechanisms for this as Boden [10] and Stiny [108].

Taura and Nagai [111] found another way of producing creative insights is '*concept blending*' where a new concept is produced by combining two base concepts, the '*blend*' inherits structural aspects of each. This is similar to Boden's idea of combing conceptual spaces through analogy, but brings a more sophisticated explanation of how two idea structures can be seamlessly and elaborately combined to create new designs dramatically different from the originals used.

From these contributions on creativity in design it can be anticipated that designer-makers may have creative episodes through similar mechanisms presented by previous research, such as using analogy, exploiting relevant emergent features and blending concepts. Finding the circumstances such mechanisms occur in making is the aim of this research.

2.5   Digital design tools

Shape grammar is just one type of generative design that can be implemented as a digital design system. This section summarises some relevant literature about digital tools and the relationships with design, making and creativity.

Glanville [42] makes a distinction between the three different approaches towards using computers in design, specifically in architecture. He assumes three characterisations of the computer in architecture, the first being the '*computer as*', the computer as part of a built

environment, envisaging smart buildings and the internet of things. The next is the computer as '*illustrating*' the now ubiquitous practice of using CAD systems to produce plans, drawings and virtual reality representations of buildings. The third is the computer as '*making*', a more exploratory, experimental approach to their use in the hope of finding something novel. Glanville also defines two attitudes in computer use, that of the computer as a '*tool*' or '*toolbox*' where the expectation is that the tool perfectly fits and performs a certain task. The second attitude is viewing the computer as a '*medium*', this is where there is a relationship between computer and user; a back and forth conversation that informs the course of what we are doing, where tools can be hacked and misused. Glanville claims this is by using this second approach a more creative outcome is likely. For this to happen Glanville claims one must '*listen*' to the computer, dropping preconceptions and breaking away from standardised tool kits.

Fisher [37] has carried out research into the possibilities of digital tool making for architects, looking at using algorithms taken from biological analogies and if these could be used for '*novelty generation*', assumed to be an alternative expression for creative outcomes. He found that giving digital tools he designed did not encourage novelty generation by students asked to use them. He realised that the tools already had the design knowledge embedded within them, and were too prescriptive, already defining the designs and not leaving room for any new '*un - encoded*' discoveries that would be desirable for creative outcomes. He suggests that digital tools either have to support a rich variety of actions, like their analogue counterparts, or that the designer must be involved in the actual tool making process for any hope of a novel outcome.

Another researcher in the area of architecture to tackle similar themes is Frazer [39] whose book *An Evolutionary Architecture* discusses taking analogies and processes inspired by biology for form finding for architectural projects. He claims this reframes architectural practice, with architect not as designer, but as initiator of processes of growth and evolution. This idea seems to have much in common in the philosophical ideas of Ingold [50] previously discussed

in the literature review, whereby things are brought into being by interacting with a flow of materiality.

Rivka Oxman [85] tries to establish a theory for '*the first digital age*' in the context of architecture, by sorting digital design interactions into three categories, that of interacting with a digital sketch or drawing in a CAD programme, interacting with a preconceived generative mechanism to generate designs and interacting with the actual generative mechanism on an operation level; building or fundamentally adjusting the workings of the mechanism. The language Oxman uses to describe the use of generative design, signals the similarities to craft practice; she uses words and phrases such as '*medium*', '*formation processes*', '*digital matter and material*'. She even proposes that educators should look to the Bauhaus's foundation course as inspiration for a new pedagogical digital design framework with the principles of '*bi-polarity of formal concepts alongside material imperatives*'.

That the way we work with digital technologies is analogous to craft practice is not a recent line of thought. Malcolm McCullough's book *Abstracting Craft: the practiced digital hand* [77] from 1998 lays out such a theory. He points out: '*Explorations of generative structure obtain power from hand, eye and tools. They arise from personal knowledge, practice and commitment of the sort found in traditional handcrafts, now applied to symbolic system*'. He demonstrates that those who work with digital technologies, particularly CAD programs are craftspeople, making use of their hands, eyes and tools.

Computational design tools can also have detrimental effects on design processes, Robertson and Radcliffe [90] found three of these effects: '*circumscribed thinking*', when the limits of a tool are in turn allowed to limit design alternatives; '*premature fixation*', when the designer resists making changes that seem too difficult; and '*bounded ideation*', when technical problems with computational tools negatively restrict the designer's development of a design. All three can detract from the exploration of design alternatives, and one would expect from the potential of creative episodes.

Much of the discourse on digital design systems uses the language and analogy of traditional crafts. The authors propose that generative design mechanisms in particular provide a different experience for the designer than paper based sketching or straight forward computer aided drafting. Most digital design systems are used to define the geometry of objects, so perhaps it is not surprising to find similarities with making, which is about form giving. The themes of tools, material and making appear throughout shape grammar and digital design literature, making a strong case that shape grammar is a relevant device to explore the processes of designer makers and the way new digital fabrication tools can be used

2.6   Computational making

Recently, access to digital fabrication tools such as laser cutters, CNC milling machines and 3D printers has provided designer-makers with new ways to produce objects, this has led to a new culture of digital making.

Digital tools and fabrication have been embraced by the academic designer-maker community, providing fertile ground for new practice based research from the early 2000s. Of note is the Autonomatic research group the University of Falmouth [7], a cluster of designer-makers researching the role of digital fabrication technologies in designer-maker practice. Leading the cluster, Katie Bunnell's [15] research has been concerned with the opportunities for integrating digital technologies with ceramics techniques and in particular the opportunities provided by digital fabrication for consumer customisation.

Drummond Masterton [74] was also part of this cluster, a traditionally trained metal smith who has embraced digital fabrication, particularly computer controlled milling. Masterton found the standard software tools available to him to be detrimentally restrictive, producing objects he thought too homogeneous to be truly perceived as artistic craft pieces, his chosen domain. Masterton sought to find ways to make more distinctive objects by gaining a deeper understanding of how the machines were controlled, and began to hack into the various codes

that controlled the milling machine to subvert it for his own ends. The results are artefacts with subtle yet richly patterned surfaces which have a distinctive of characteristic aesthetics.

Justin Marshall has not only used digital fabrication to make objects but has employed generative techniques alongside this [73]. The generative aspect was used to allow a consumer to have some control of the form of the finished object on a web based application. Units were allowed to randomly fill a '*mould*' in a relatively '*unsophisticated*' generative system. In the paper the emphasis is on the link to craft via the individuality of the objects produced and small scale production rather than the making and designing processes.

A conference on digital making was held at Falmouth in 2014, attended by the author, called *All Makers Now?*' [70], the proceedings provide an insight into the plethora of digital fabrication research projects being undertaken by craft based design academics mostly based in art and design schools. A previous conference of the same academic community, such as the *New Craft: Future Voices* [38] international conference in Dundee in 2007 the discussion centred on if digital processes could legitimately be used by the craftsperson. At the *All Makers Now?* conference this debate seemed to have faded, a view that digital tools are tools like any other has been accepted by these craft academics and the discourse moved on to what making can bring to the digital world and what the digital world can bring to making, in terms from aesthetics, production to social concerns. However, this community has not addressed the links between tools, rules and creativity in design and making processes, something this thesis hopes to demonstrate.

In architecture there has long been a disjoint between the architect and the makers, or builder of buildings. Many architects have seen the digital fabrication techniques as a way of being more closely involved in making buildings. The Fabricate [44] series of conferences brings together researchers in the field of architecture who are investigating new fabrication techniques, mostly by directly experimenting with new digitally controlled manufacturing equipment to empower them to make parts of or material prototypes buildings themselves.

The emphasis in this community is on design through making, exploring new possibilities, rather than the traditional preparatory drawings of architecture.

In the MIT Architecture department there are a number of researchers investigating computation and digital fabrication. In particular Neri Oxman [81] has developed a philosophy of man-made materials that find form according to their environment; the notion is that in the future materials will compute forms, generating objects fit for purpose through embedded properties and environmental forces. This is not a reality yet, but she has simulated this idea by using generative design tools, based on biological systems and aesthetics, to generate geometric representations which have been multi-material 3D printed to mimic the formation processes she proposes.

Since the research towards this thesis was begun, Stiny and Knight have turned their attention to computational making [63], leading a research cluster founded in 2014. Knight [63] has suggested a switch between the earlier approaches of shape grammar, where material things were viewed through the lens of shapes to a new approach in which shapes are viewed through the lens of material things.

A special issue of the journal Design Studies edited by Knight and Vardoulli [64] titled *Computational Making,* published in 2015 brought together papers on the subject, establishing it as topical research theme and heralding a move to apply shape grammar theory to making practices. Knight and Stiny [65] propose in a paper in this issue that shape grammars can be used to describe making processes, and term these making grammars, transferring the sketching and seeing of shapes to the doing and sensing of materials, and present some examples of such grammars based on drawing, knot making and water colour painting. These initial definitions provide confirmation that other researchers agree that shape grammar could be a useful way of describing making practices, but as yet a more detailed look at successful designers using making processes and the mechanisms of this has not been investigated by this community.

2.7 Research questions

The literature has shown that designer-makers and their design processes have been underrepresented in established design theory research, in which an emphasis on sketching and abstract cognitive reasoning with various design representations has taken precedence.

Recent thinking in the architectural and craft research communities has expounded that computational and digital fabrication processes have much in common with traditional making. This thesis assumes the hypothesis that shape grammar may be an informative link between making and creativity, as similar concepts appear in these spheres; such as rules, transformations, emergence and tools.

By making an analogy between tools and shape grammar rules this thesis seeks to examine whether shape grammar can support creative making in a designer-maker context. The hope is that shape grammar can provide models to describe and inform activities by designer-makers, in order to contribute knowledge about strategies designer-makers could use to improve the likelihood of successful design-through-making practices. Shape grammar has been used in two ways in design research previously, as a theoretical way of describing and modelling design processes and as a generative design method, these two distinct roles are examined in two parts to this thesis, with the overarching question: **Can shape grammar support creative making?** This can be split into a number of sub and complimentary questions:

Part 1: Can shape grammar help define creative designer-maker practices?

How and when do creative episodes occur in designer-maker practice?

Can shape grammar be used to model and describe designer-maker activities?

Can shape grammar help define strategies for the designer-maker to increase the likelihood of creative outcomes?

What can shape grammar theory gain from comparison with designer-maker practices?

Part 2: Are shape grammar weights a useful way to generate creative designs for multi-property 3D printing?

Can a shape grammar weights be used to generate designs for multi-material 3D printing?

Can using shape grammar weights provide opportunities for creative episodes?

Can shape grammar weights theory gain additional ideas from exploring this particular application?

3 METHODOLOGY AND METHODS

This section explains the methodological approach taken to answer the research questions posed in the previous section.

3.1 Design research methodology

Frayling [36] categorised design research as being divisible into three separate modes of enquiry, these were '*research for design*', '*research about design*' and '*research through design*'. These categories were later taken by Peter Downton [30] and explored in more detail to create a guide of how these can work in practice. A synopsis of these now follows.

Downton [30] describes '*research for design*' as a process of gathering information to support and enable a design project. This is the ground work done by designers to gather relevant material from the field of design and other relevant fields by bringing together literature, data and objects which may provide useful information for the design process.

The next category '*research about design*' is the action of examining how and why design and designers operate. This incorporates history of design research, but is also where the established design research community that developed from the 1960s onwards resides, the history of which is discussed in section 2.2. This initially concerned with finding prescriptive scientific style methods for designing, it later became more focussed on trying to discover more flexible models of the way designers work with the intention of improving designers' practices and education. This later research uses methods from the social sciences, interviews with designers and observation, researchers attempted to analyse designers' actions using protocol analysis techniques, to draw out models which may inform design practice more widely.

Thirdly '*research through design*' is a third, newer idea of design research coined first by Frayling [36] and classing the design process as an actual research method in its own right, covering

research sourcing new knowledge about the use of materials, technology or by documenting a design process as part of an action research project. Downton [30] goes further in suggesting that designerly knowledge is different, yet not inferior, to the accepted idea of scientific knowledge, and new design knowledge is a valid form of academic knowledge. Design uses knowledge, personal and collective but it is embodied in the design process, making it harder to analyse and examine than scientific knowledge.

Glanville [42] argues more broadly that scientific research is actually design itself, an iterative process of designing and redesigning experiments and theories by participants, contrary to what traditional research science would attest, also supporting the case for '*research through design*'.

Tim Ingold is a key contributor to making research, in his book *Making: Anthropology, Archaeology, Art and Architecture* [50]. He uses the term the '*art of inquiry*', and states:

'*In the art of inquiry, the conduct of thought goes along with, and continually answers to, the fluxes and flows of the materials with which we work. These materials think in us, as we think through them. Here, every work is an experiment: not in the natural scientific sense of testing a preconceived hypothesis, or of engineering a confrontation between ideas 'in the head' and facts 'on the ground', but in the sense of prising an opening and following where it leads*' [50, P6-7]

This description has much in common with Glanville's account of how scientific research is really achieved, a process of tweaking and tinkering, influenced by the researcher until something is found, which is then post rationalised. Research itself is a kind of making; a making sense of the world.

Action research, a well-established research methodology in social science and has many similarities with design research methodology [52]. Action research is carried out by insiders within a community to elicit some kind of action or change to practice [46] and has been widely used in business and management research to investigate how underlying, often tacit,

concepts are manifested in practical situations. Participant observation is a specific form of this, where an insider studies their own practices [46]. The idea is to make a plan, put this plan into action and then observe the results [46].

A similar approach is that of '*naturalistic inquiry*', part of a post-positivistic research paradigm developed by Lincoln and Guba [69]. Post-positivism takes into account the complex and subjective nature of human activity and interaction and the view that realities are constructed. The aim is to carry out research in a natural setting, where the phenomena would normally occur, not in a laboratory. In this case the natural setting is a studio/workshop environment and the practice of the author. Naturalistic inquiry takes into consideration that the context provides '*constant mutual shaping*' of the phenomena that take place [69]. Also the researcher elects themselves as the primary data gathering instrument as only a human is capable of understanding fully the complex interactions that take place, such as the reflection-in-action in a design process. Also the methodologies in such research are emergent, they grow and unfold through the undertaking of the project. Crucially criteria to test the trustworthiness of any findings also have to be established by the researcher.

3.2   Methodology used for this research

The research questions in this thesis fall into two main areas. The first is to examine what role tools and materials play in the creative episodes and use shape grammar to bring insights to understand this role. This falls into the established category of '*research about design*', and can employ conventional methods from design research. On this basis it was anticipated that the best way to gather evidence about designer-maker activities was to interview designer-makers about creative design-through-making processes they had undertaken.

The second area of inquiry is intended to bring new knowledge to the field of digital making, to discover if weighted shape grammars are a useful way to generate designs for multi-property 3D printing. This part of the research is also '*research about design*' but also

methodologically was carried out as '*research through design*', a pragmatic approach of carrying out design processes in order to gathered new theoretical and designerly knowledge.

Owen [86] presented a model of how a knowledge base is assembled, the aim of research, in an article in Design Studies. Owen describes how this occurs in the analytical and synthetic realms of different disciplines and how each realm contributes to new knowledge. His general model can be seen in Figure 3-1, the analytic and synthetic approaches contribute to knowledge on a subject in different ways. Analytic knowledge building takes place through a process of inquiry, generating and evaluating theoretical proposals. Synthetic applications build knowledge by applying known principles in works which in turn can generate new knowledge.
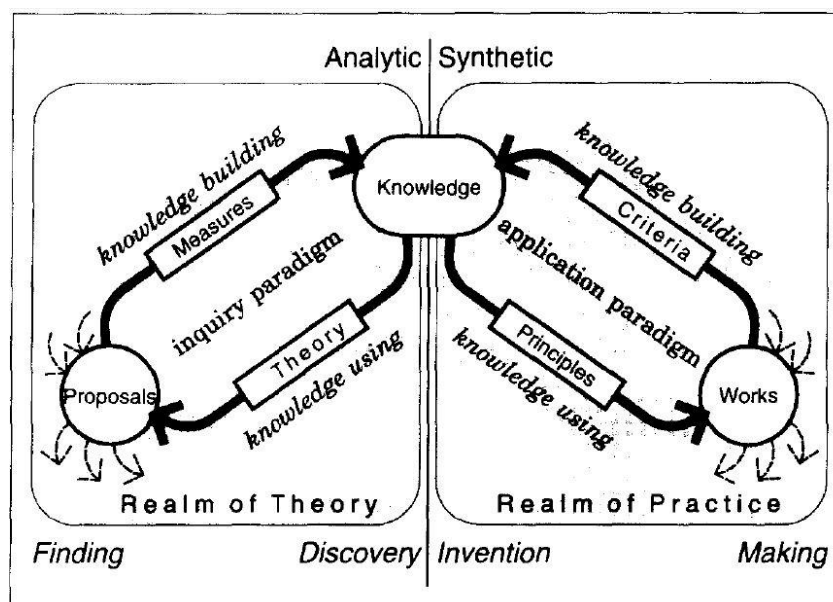
Figure 3-1: Owen's model for accumulating and integrating knowledge in the analytical and synthetic realms

To answer the questions relevant in this thesis knowledge will come from both the analytical and synthetic activities of design research, a methodological model based on Owen for this thesis can be seen in Figure 3-2.
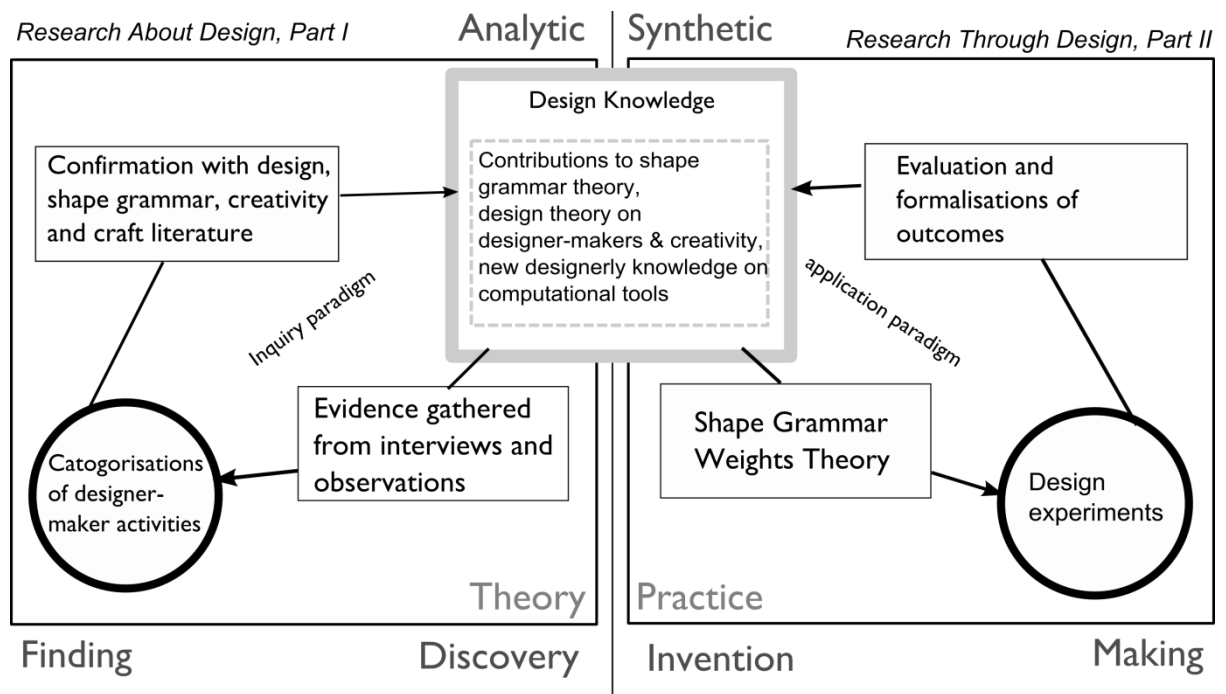
Figure 3-2: Methodological model for this thesis based on Owen

Part I of the thesis takes place primarily in the analytical realm and can be termed '*research about design*'. This method of inquiry begins by gathering evidence from interviews with designer-makers and observations from the author's own practice. This evidence is then surveyed for activities related to creative episodes that can be categorised, a process informed and confirmed by related literature, and compared to models from shape grammar theory. A detailed protocol analysis of a computational making process carried out by the author is undertaken, using shape grammar to model the activities, gaining further insights for the research questions.

These research activities will produce new knowledge about designer-maker's creative episodes, offering useful knowledge in the form of strategies for designer-makers who wish to aim for creative outcomes. It will also provide new knowledge to contribute to shape grammar and design computation theory in the synthetic realm.

Part II of the research concentrates on the synthetic realm of design, and comes under the heading of '*research through design*'. This is a process of carrying out a design process to

produce new knowledge about, in this case, design, and specifically the application of shape grammars and multi-material 3D printing. Again the process begins with pre-existing knowledge, the principles of shape grammar weights. From this some ideas are developed about how shape grammar weights can be used in conjunction with multi material 3D printing and design processes carried out to prove and evaluate the usefulness of such an approach through design reasoning and applied design experiments.

By carrying out design experiments naturally situated knowledge about the usefulness of shape grammar weights for generating designs for multi-property 3D printing can be found. These findings will be of use to others working in the field of computational making and digital designer-makers as designerly knowledge, a valid form of knowledge contribution [30]. New theoretical ideas relating to shape grammar weights will also be developed from putting current theory into practice in the design experiments, providing knowledge contributions that may be useful more widely in design.

Some of the outcomes of this research activity will be physical objects, computational tools, 3D printed samples and design objects demonstrating the ideas and possibilities of this approach. Rust et al. [91] define several ways in which knowledge can be found in or through an artefact, paraphrased as:

- Simple forms – demonstrates a principle or a technique

- Communication of a process – making a process explicit

- Artefacts within research – that are instrumental in communicating ideas or information

- Knowledge elicited by artefacts – artefacts provide a stimulus or context which enables information to be uncovered

As Rust et al. [91] suggests the 3D printed objects produced by the design experiments will foremost demonstrate the principle and technique of using shape grammar weights as a way of generating designs for multi-material 3D printing, they also have potential to make this process

more explicit to the reader. Any knowledge resulting from the physical objects will be formalised into written knowledge about the application and theory of grammars and creativity.

3.3   Possible methods which have been ruled out

There are other methods which could possibly answer the questions posed for this research, an examination of some of these is now presented and an explanation of why they have been discounted.

Using direct observation of designer-makers could also be a way of finding out the relationship between tools and creativity. However creative episodes can occur at any time, it is unlikely an observer could be present to witness such crucial moments in a design process, which can take months, therefore an interview at the end of a design project is a more realistic undertaking, despite issues relating to memory and post-rationalisation.

Using controlled group experiments was also considered: giving a group of designers some tools and materials and giving them a design task to carry out over a short time period that could be closely observed and hoping that some creative outcomes were achieved. This was also ruled out as real-world design processes and creative endeavours are usually carried out over long periods of time, high level creativity requires immersion and incubation [24] and the author wished to have as truthful a reflection of designer maker practice as possible, where designers may perform complex, skilled and time consuming transformations on tools and materials, rather than cursory designs that would occur in only a few hours experimentation.

Part II of the thesis can only feasibly be carried out as '*research through design*', discerning whether the practical application of shape grammar weights is feasible and useful for generating designs for multi-material 3D printing requires the application to be carried out in realistic design experiments. Different software and 3D printing materials and systems could be used, those employed are commonly used by product designers and were familiar to the researcher,

so were a logical choice. The findings can be represented with written, notated and visual descriptions and can be interpreted by designers into their own computational systems if required.

PART I - FRAMEWORK OF STRATEGIES FOR STIMULATING CREATIVE EPISODES

To explore how shape grammar can be used to support creative making Part I (Chapters 4, 5, 6, 7 and 8), examines if and how shape grammar theory can be used to model designer-maker design processes. Data gathered from design processes was analysed through the lens of shape grammar theory to produce a range of strategies for stimulating creative episodes, which in turn may be useful for designer-makers.

4   DESIGNER INTERVIEWS

To discover how designer-makers use tools and materials in their design processes the best approach was to interview a range of such designers about previous projects they had undertaken that they felt had been successful.

The interviews were loosely structured with a range of questions about the designers' practice generally and then more specifically about tools, processes and creative ideas, whilst trying to avoid any influence from the author's knowledge of shape grammar, rules and tools. No particular hypothesis had been formed at the interview stage by the author. To try and elucidate on complete design processes the author asked the designers to, but not exclusively, concentrate their answers on a particular project they had undertaken.   A list of the questions taken into the interview can be found in *Appendix 1- Questions used in designer interviews*, these provided a loose structure for the researcher to keep the conversation relevant.

4.1   Collection and analysis of interview data

The designers interviewed are a small sample, targeted specifically for their apparent approach to design; working directly with tools and materials to design, rather than approaches such as sketching or design reasoning.

Once identified as possible interviewees the author asked the designers to meet and discuss some of their previous design projects at a location of their choosing, no incentive was offered. Permission was sought to record the conversations with a view to the data gathered being analysed and used for this research. The data being collated in the interviews was not considered to have any particular ethical implications or sensitivities in the general domain or for anyone involved and so was deemed 'no risk' from an ethical standpoint. As the interviews were carried out on a general level of discussion about successful design processes and were not of a sensitive nature it is likely that the data collected was a fairly accurate reflection of the designers' working practices.

Unfortunately retrospective reflection by a designer on work they have carried out may not be entirely accurate due to memory issues and post-rationalisation of narratives in the design process. These factors cannot be removed by the researcher, but being critically aware of this possibility is pertinent. Interviewees also may consciously or subconsciously misrepresent aspects of their answers depending on how they want to be viewed by the interviewer. Again this kind of subjectivity is to be expected and is accepted as long as the researcher is critically aware of such factors. All of the interviewees were well known to the author and in this case the author's position as an insider hopefully allowed deeper insights and elicited trust from the interviewees.

The author transcribed the interviews from the recordings to enable qualitative analysis of the data gathered. The author searched for examples of tool activities in the transcripts, looking for the significant moments mentioned by the designers that informed the final designs, simply coding these by marking for closer examination. These episodes were then sorted using

Boden's framework of creativity [10], which offered a rational way of looking at creativity in terms of tools and rules, this allowed the categorisation of tool activities into uses, combinations and transformations. Tool transformations were further categorised into more detailed categories using concepts from a variety of creativity literature. Finally these categories were analysed in terms of shape grammar theory, to produce a framework of strategies for stimulating creative episodes for designer-makers.

This evidence was bolstered with further evidence from existing design research and practices to produce the findings discussed in chapter 8, each section discussing the categories of creative tool use found in the interviews.

4.2   Designer profiles

A summary of the designers interviewed now follows to give the reader an overview of their practices. The interviewees were selected on the basis that they worked closely with tools and materials in their design processes. Within this context a range of designers was sought between those who use analogue tools and those who use digital tools.

4.2.1   Ian McIntyre

Ian McIntyre is a designer and maker [79], who in recent years has focussed on designing ceramic tableware for industrial production, working on a freelance basis with home-ware companies Another Country and HAY, one such range can be seen in Figure 4-1.

McIntyre designs by making his own full ceramic prototypes for production and some of his finished products in his studio. In his studio he has tools used in industry, jigger-jolly machines, which he uses to make prototypes exactly as they would in full scale mass production. This is not always the method employed by tableware designers, from experience of internships that McIntyre had undertaken he had found most tableware designers work by making foam models and computer aided design drawings despite the major difficulties in translating such

representations into ceramics. McIntyre prefers to work directly with the manufacturing tools and materials of industry to design and described this as '*design through making*'. He found this a more efficient process, as translation from prototypes was smoother than more abstract representations of the designs. He also found that insight into the actual production methods offered him better opportunities to for design creativity, trying to directly manipulate the production processes offered new, yet achievable designs.

Figure 4-1: Series One Pottery for Another Country by Ian McIntyre, 2011

4.2.2   Eleanor Bolton

Eleanor Bolton is a jewellery and product designer and maker. Her current jewellery collection [11], is a range of fashion jewellery made from cotton rope, an example can be seen in Figure 4-2, sold in range of high end design shops and fashion boutiques worldwide.

Eleanor has developed her own technique to make her work, a method of coiling and stitching cotton rope. She designs and produces all her products by hand and currently does not use any industrial production processes. It was on the development of these coiled pieces during Bolton's MA that the interview focussed upon.

Figure 4-2: Coiled Rope Necklace by Eleanor Bolton, 2010

4.2.3 Kathryn Hinton

Kathryn Hinton is a designer and silversmith [48]. Hinton has two strands to her practice. The first comes from her more traditional training as a silversmith and jeweller, this work is planned with sketching, rooted in conceptual ideas and is produced with traditional hands-on silversmithing techniques. An example from this body of work can be seen in Figure 4-3, part of Hinton's 'exhausted' utensils range, where archetypal utensils appear to bend and flop playfully onto to tableware, at odds with their usual inert stance and rigid material nature.

Figure 4-3: Exhausted Cutlery by Katherine Hinton, 2009

Hinton's second body of work was developed towards the end of her MA and throughout her MPhil at the Royal College of Art. She had an idea to develop a digital silversmithing hammer, a device to translate the movements of silversmithing into something a computer could interpret. The result was a haptic digital hammer with internal motion sensors that plugs into a computer via a USB port and works in conjunction with computer modelling software. Hinton makes silverware and jewellery using this tool, the pieces are formed in a digital environment and then made into physical silver pieces with digital fabrication techniques such as rapid prototyping and CNC milling.

4.2.4 Marina Brown

Marina Brown is a freelance web designer, specialising in Flash animation for banner adverts [14]. Brown works freelance for media companies, working on digital advertising campaigns for television programs. Depending on the job she often contributes to the initial creative development of campaigns as well as the actual production of Flash banner ads, which are produced on the Adobe software Flash. Brown also does hand drawings in black and white to communicate advertising layouts to clients, known in the advertising industry as '*scamps*'. The interview centred on a particular project Brown carried out to produce a Flash web advert for a new David Attenborough program on the Eden channel, a screen shot of which can be seen in Figure 4-4.

Figure 4-4: Screen shot of Flash advert for Eden Channel by Marina Brown, 2011.

Jasleen Kaur is a designer, maker and artist whose work is inspired by her British-Indian heritage, she makes objects which inquire and comment on the intersection of these cultures. Kaur trained as a jewellery designer but has progressed to a range of work from functioning objects and art pieces, focussed on how people make and use things. In the interview two main pieces of Kaur's work were discussed, a product which went from an initial idea during her MA all the way to market, retailing in shops including John Lewis, the Tala curry measure, as seen in Figure 4-5. This is a twist on the tradition Tala cook's that acts as a three dimensional recipe, enabling the user to measure ingredients easily to make various Indian meals cooked by Kaur's family.

Figure 4-5: Tala Curry Measure by Jasleen Kaur, 2013

Also a more ad-hoc, working tool she made as part of her MA, a chai tea stall with equipment designed for one person to distribute chai tea, was discussed. This was a tool made by Kaur to solve the problem of pouring a cup of tea from a large pot efficiently and also with some humour and spectacle, see Figure 4-7.

Figure 4-6: Chai Tea Stall by Jasleen Kaur, 2011

Figure 4-7: Chai Tea Dispenser by Jasleen Kaur, 2010

5 DESIGN WORLDS

The first question put to the designers was to describe themselves and what they produced in as much detail as possible. All the designers spoke at length about this and referred back to it during the interviews, revealing that where they were positioned within design communities was very important to them and seemed to dictate many of the constraints they applied to their design processes.

To unpick this reoccurring theme it is useful to examine some concepts from design driven research and some of the literature from chapter 2 in more detail. The procedure of building or formulating a design domain or space appears regularly in design theory. Schön [93] describes designers as working within '*design worlds*', constructions of objects and relations (termed '*materials*') that designers use to frame design solutions, these range from personal principles to shared philosophies from design communities. These concepts are probed and reconstructed; then the designer observes the results, having a '*reflective conversation*' with the materials of the design world. Dorst and Cross [29] proposed that separate problem and solution spaces are co-evolved until the designer finds a suitable linking idea, usually achieved by making use of new, usual information that they use to form what they think to be a creative answer to the brief. Darke [25] proposed a similar idea with that of the '*primary generator*' a principle or set of principles which designers adhere to in their design processes to give them a starting point which in turn is used to generate possible solutions to a design problem.

Similarly the world of craft is made up of material disciplines; these are often defined by the materials – ceramics, textiles, woodwork. Dormer [27] states that craft activity '*follows rules, conventions and patterns*', again this presents the idea that craft making requires sets of known constructs that someone must learn and use to produce something creative. Traditionally crafts people specialise in one of these craft worlds, using combinations of the rules, tools and materials to motivate the making of objects.

The same ideas appear in writing on creativity, Csikszentmihalyi's [24] definition of creativity is '*when a person, using the symbols of a given domain such as music, engineering, business, or mathematics, has a new idea or sees a new pattern*.' Boden's first specification of creativity is what she calls '*exploring conceptual spaces*'; searching within formalised sets of rules for new possibilities. She considers this search as taking place in the mind, describing it as a metaphorical map of terrain to be explored, where certain stylistic rules are followed to create works, but also define a problem to be solved.

Shape grammar is a way of defining set of relations of shapes, a geometric design world. Research, such as that done by Koning and Eizenberg [66] and Cagan et al. [75,76,88], looked at how new designs could be created from known sets of geometric style rules. Recently Knight and Stiny [62] have extended shape grammar theory to include making grammars, set of rules describing making techniques.

There is a consensus in the literature from these different fields that creative works come from the exploration and use of rules in a design world, albeit the two terms '*rules*' and '*design worlds*' are interchanged with similar constructs such as '*conventions*', '*structures*' and '*conceptual spaces*', '*domains*'. For the purposes of this thesis it is useful to call these entities '*rules*' and '*design worlds*' as they fit with the intentions of the research, using shape grammar, a rule based theory to analyse designer-maker practices.

That the designers interviewed were very concerned with their position in design communities and the associated conventions is unsurprising on review of well-known design theory literature, it is accepted to be an essential part of framing design problems and solutions. On a higher level the designers discussed various shared design worlds that they were part of by a title they generally used; '*jewellery designer*', '*web designer*' to outsiders, but went onto describe the more specific communities they were or were not a part of and the nuanced worlds of their own personal practices. The designer-makers referenced various rules and conventions they adhered to, however their attempts to define themselves were dominated by the

specification of tools and materials. This is perhaps what sets designer-makers apart from other designers, they dedicate their design practices to a particular set of tools, materials and associated techniques and use these as the primary source of generating designs.

5.1   The role of tools in designer-maker design worlds

The interviewed designer-makers' personal design worlds were principally defined by tools and their associated materials. Conversely tools and materials allowed the designer-makers access to design communities and markets; shared design worlds, and were often selected to this end.

Ceramics tableware designer Ian McIntyre consciously selected and used specific tools to fit in to a shared design world and then find his own niche position. He had previously made what he called '*experimental products*' during and after his under-graduate studies, using various materials, these were decorative and unique pieces aimed at collectors. During his MA at the Royal College of Art McIntyre decided he wanted to change direction and design every-day, functional tableware. This involved addressing details such as functionality, capacities, ergonomics and practicalities, constraints that had not been a concern in his previous work. He also had a desire to help bolster the ailing British ceramic manufacturing industry, trying to make use of the skills available in the remaining factories. These domain decisions influenced the ceramics designer's choice of tool, the jigger-jolly machine, '*it was the closest thing we had* (in the Royal College of Art ceramics workshop) *that mirrored real life production… things are still produced on those machines in industry*'. The use of this tool also allowed him to '*design a range of products that nipped into a little gap in the market that otherwise would be incredibly hard to get into*' as he could initially produce the products himself and get them into the market while hopefully eventually having them produced in a factory with a company once he had established them as viable products.

Jewellery designer Eleanor Bolton similarly made a decision to reposition herself for the project discussed in the interview. She had previously made work from found objects with a

strong narrative and conceptual basis, such as her piece '*Decapitated Pet Jewellery*' shown in Figure 5-1.

Figure 5-1: Decapitated Pet Jewellery by Eleanor Bolton, 2008

While researching her MA dissertation on similar work Bolton came to the conclusion that '*I am not adding to this in anyway, in fact I am doing kind of bad versions of it*', she also disliked that making such pieces was '*process heavy*', applying a large array of tools and processes to produce on piece, and wanted to bring more simplicity to the manipulation of her materials. From this Bolton decided to restrict herself to a particular set of materials and tools and then finally to a single technique she had then developed: '*it was literally just, right here's a ball of yarn, here's a needle and here's the rope and I wasn't allowed to use anything else*'. From this she developed a method of stitching the cotton rope into coils by threading through the loops of the braid of the rope. The tool in this case is one of the most simple – a needle, but with it the designer's design world shifted away from the shared design world of conceptual art jewellery and into a new design world .

Initially unintentionally, Bolton also gained access and became part of another shared design world she had not previously operated in – that of fashion, due to the materials and the bodily scale to some of her pieces. This shows not only the designer may purposefully use tools as a way of entering particular design worlds, but the reverse may be also true, that tool and material selection can open up access to other design worlds unexpectedly, leading to access new useful rules. Bolton seized this opportunity and made use of this design world; teaming up

with a fashion designer to show her pieces in the Royal College of Art fashion show on graduation, participating in London Fashion week, and working with fashion retailers, stylists, photographers and press. All this while she still retains credibility in shared craft and design words, by also showing with craft and design galleries and being supported by the Crafts Council by taking part in their 'Hothouse' business scheme for emerging makers [11].

Figure 5-2: Eleanor Bolton's Rope Necklaces in French Vogue, 2010

Jasleen Kaur had a different take on where she fitted into shared design worlds. She felt that she didn't even fit in to the most general of shared design worlds to be able to call herself 'designer' or 'artist' or 'craftsperson'. However Kaur still had a very strong sense of her personal design world, inspired by the interplay between British and Indian cultural practices in her own life and an interest in how people make and cook in ad hoc ways among other things, saying that '*food was massive in culture*'. Again tools and materials played an important role in Kaur's design world; she used found cooking utensils as inspiration for designing new utensils.

It is clear from the interviews that tools and materials play a pivotal role in the construction of the design worlds the designer-makers work within. The reviewed design and creativity literature confirms that designers work within design worlds, also termed domains and conceptual spaces, and that these are made up of sets of constructs such as rules, materials, conventions and relations. However none of this literature specifically mentions or examines

that tools are an important category of these design world constructs, a crucial omission in design research to date.

5.2   Tools and personal design worlds

As Schön mentions [93] design worlds can be shared or personal. According to Boden a '*higher*' level creative activity is to go beyond searching a known conceptual space, the equivalent of a shared design world, and transforming it in some way to produce a novel conceptual space, the equivalent of a personal design world. Boden suggests these transformations can range from small changes, bending or tweaking rules, to dramatic, surprising conceptual shifts that produce whole new domains, the result being that these can then be used to define novel artefacts.

From the interviews it was also found that tools not only defined the shared design worlds the designer-makers accessed but also played an important part in their personal design worlds.

Once certain tools and materials were selected the designers tended to adhere to these choices even if in theory they could have chosen to change them. This agrees with the findings of Eckert and Stacey [33] who found that designers in under-constrained domains, in the case of the research knitwear designers, found it useful to use self-impose constraints to help them move towards solutions. McIntyre, Hinton and Bolton were all describing self-motivated design projects where they could evolve both problem and solution with a great amount of freedom. Marina Brown was the one designer who worked to commission for corporate clients, so she was tightly restricted to using one particular tool for production, Adobe Creative Suite, in main the Flash Professional animation software and had the most strictly defined design briefs.

Tools for the designer-maker are entities used to produce and process materials to generate both prototypes and finished objects. McIntyre used tools in the most conventional sense, in particular the jigger-jolly machine, to directly hone and shape plaster and ceramics into suitable

forms. Bolton used a single, ubiquitous tool, a needle, however the tool that made her distinct design world was the hand stitched coiling technique she developed that generated each piece of jewellery. Hinton's primary tools, as a silversmith, were hammers, her hammers for shaping silver in the traditional way, but also her digital hammer for shaping digital materials that were then reinterpreted in physical materials by way of digital fabrication. Brown also used digital tools, standard digital software to produce standard digital media. Kaur used cooking utensils as an embodiment of cultural activities and used these to make new tools for sharing these cultural activities. From just these five designer-makers we can see that not only were tools important to their personal design worlds, but that the term tool covers a range of objects made, used and referenced by the designer-maker, to transform materials; physical, digital and conceptual, to produce design outcomes.

5.3 The role of tools in creative episodes

The interviews with the designer-makers revealed the importance of tools in their shared and personal design worlds and a range of classes and applications exist. The designer-makers tended to restrict themselves to a few tools, but their use of the tools was very varied and experimental.

Experimenting with tools often lead to design creativity, tools featured in creative episodes in the making processes, similar the '*creative leap*' [29] described by Dorst and Cross, the designer-makers successfully solved design problems in a novel and useful way by co-evolving design goals and their tool use.

The following sections discuss interviewees and the author's descriptions of creative episodes in their practices where tools were involved, established concepts from design and creativity literature, particularly Boden's computational view and shape grammar, enable these activities to be categorised into types of tool activity that may yield creative episodes.

5.4 New tool combinations

Some creative episodes the designer-makers described occurred through new combinations of tools; tools that were not conventionally used in the shared design worlds that the designer-makers transferred into new design worlds and put to use in new ways.

An example arose in the author's own design practice, a hybrid digital and material based practice. For an MA project the author used freeware software program Jenn3D, '*a toy for playing with various quotients of Cayley graphs of finite Coxeter groups on four generators*' [6] in other words a visualisation tool to view complex mathematical geometries in higher dimensions, Figure 5-3 shows a screenshot of the programme. It allows the user to visualise, manipulate and crucially export complex three dimensional structures in a format suitable for CAD programs. The author appropriated the tool for her own use in her design world, enabling her to bring complex geometric structures otherwise not seen or possible in traditional jewellery making.

Figure 5-3: Jenn 3D Screen Shot and jewellery created with the help of the program

Arguably Eleanor Bolton also did this in her use of hand stitching, usually used to join or decorate fabric, is not something commonly done in rope based craft, more often techniques like braiding, weaving, knotting, wrapping or macramé are used to join and manipulate rope. Bolton redirected a tool, the process of hand stitching, into a new design world, rope manipulation

Figure 5-4: Eleanor Bolton sewing rope together with needle and thread

Digital craft researcher Drummond Masterton also reports in his research that to try and achieve unique surface patterns on his CNC milled aluminium bowls that break away from the standard appearance of CNC milled objects he distilled his designs through several different software programs. He used some of the processes in these pieces of software in a different way from which they were intended, such as disrupting automated tool paths for aesthetic gain [74].

Designer-makers regularly commandeer tools from outside shared design worlds, to form a personal, niche design world. This is a procedure of assembling novel groups of rules to be used together to generate designs, as would occur in a shape grammar design process. It also echoes Boden's definition of creative activity, that of building new conceptual spaces to guide the production of novel artefacts.

6 TRANSFORMING TOOLS

As discussed in the previous sections new creative design worlds can be formed by combining and using tools in new and unexpected ways. In addition examples were found in the interviews, the author's practice and other research of makers transforming tools to attempt to find new ways of making.

Boden's description of creativity suggests that exploring and transforming the rules of a conceptual space is a creative activity, if tools can be viewed as embodiments of some of the constituent rules of a design world, then transformation and manipulation of tools would in turn be a valid creative activity. Indeed different types of tool transformations and related creative episodes were discovered in the interviews and reflection on the author's own practice, these are now described.

6.1 Tool variable transformations

Designer-makers modify tools that exist in their design-worlds, one way of doing this is altering extrinsic variables of a tool.

An example of variable change on a physical tool is to transform the shape in some way, in turn transforming the effect it has on a given material. Kathryn Hinton described the common practice of altering tools to suit the needs of the maker in silversmithing; stakes and hammers are shaped by the craftsperson to suit different making jobs. She says: '*I guess with traditional* (silversmithing) *tools you adapt them, if it's a stake that's not right for your job you file it until it gives you the right shape…… you shape hammers and cut them or take off the sharp edges*'.

Ceramics tableware designer Ian McIntyre also described a similar feature in a project he had undertaken. He made uniform cylindrical plaster moulds to cast porcelain vases, and then individually chiselled into each one creating a different profile, this process can be seen Figure 6-1. The aim of this was to produce more valuable individualised products, unusual in cast

ceramics, whilst still using a common and straight forward production process. McIntyre reshaped his tools – in this case the moulds, as a creative design activity.

Figure 6-1: Broken Vase Process, Ian McIntyre, 2008

Variable transformations could range from calibrations that conform to the tools design, such as selecting variables on a CAD tool or the shape or size of a physical tool, such as changing the radius when using a pair of compasses. Boden [10] specifies that exploration and transformations of sets of rules are creative activities, activities that could be aligned with variable transformations of tools exemplified by the designer-makers. Knight [55] and Chase et al. [3, 17, 18, 54] suggested that shape grammar rules could be transformed to create new design languages. Stiny [109], also suggests parametric rules that allow for parametric variation in the transformations, permitting the idea that a shape grammar rule can contain transformable variables.

6.2   Tool function transformations

Extrinsic transformations on a tool are one way of changing the results of their application on material, transformations on an existent tool in the designer-makers design world. More complex transformations can take place using intrinsic transformations, deeper transformations that transform and reformat the workings of a tool.

Kaur intrinsic physical transformation of tools in her design process of a Chai Tea Dispenser in Figure 4-7, a '*problem solving*' exercise in the design of her Chai Tea Stall, pictured in Figure 4-6. Two metal funnels and a pair of large metal tongs and other pieces were reworked into a dispenser to scoop tea and strain into a cup using one hand. Kaur combined ready-made tools to construct a new tool concept, reversing the action of the tongs, and attaching two funnels, the top of which had been cut and filled with a silicon stopper and then perforated with holes to allow straining when opened. A rubber band between the two provides the tension. The tool works well for the purpose it is designed for, the physical realisation of this new tool is ad-hoc, a culture and an aesthetic that Kaur intentionally celebrates in her work, but is an example of intrinsically transforming the functionality of ready-made tools by reformatting them into a new tool that solves a design problem in a novel way.

One way to perform intrinsic transformations of tools is to manipulate conceptual representations of tools and manipulating these into a new tool concept that in turn can be realised and used in making processes. Jasleen Kaur transformed a tool in this way when she designed the Tala curry measure, a product that allows a person to measure out ingredients for various accompanying curry recipes with ease. Kaur had acquired a vintage Tala Cook's Measure from a market, and then found that it was actually still in production, pictured in Figure 6-2.

The Tala Cook's Measure is a metal cone, printed on the inside, see Figure 6-2. Each printed column lists ingredients with similar densities, with a dedicated scale for measuring out equivalent weights of these. The functionality appealed to Kaur as it reminded her of the way she and her family measured ingredients for family recipes, using familiar cups and spoons of unspecified volumes as bespoke measuring utensils in an intuitive way. The first cook's measure she procured was a vintage version and had ingredients unfamiliar to her on it, such as tapioca, so initially Kaur thought of updating it to work with the kinds of ingredients she regularly used. Although she later discovered the measure was still in production and updated, Kaur developed this idea further, to a conceptual remapping of these columns as recipes and the scale makers as ingredient weights, see Figure 6-3.

Figure 6-3: Inside of Tala Curry Measure by Jasleen Kaur, 2013

Initially Kaur altered the measure with a laminated insert for the product testing phase, this constitutes a transformation of the tool function, a kind of ad-hoc transformation of a ready-made tool which was then eventually assimilated into a refined tool for making her family's own recipes.

This strategy of hacking tools, by making intrinsic functional changes, also appears in the author's own design work. The nature of many digital tools allows the underlying code to be altered fairly easily to create new versions; a functional change in a computational tool is one that alters the fundamental algorithm or rules of the tool, going beyond superficial changes in variables. Digital tools like open source programming language Processing and algorithm editor for Rhino 3D, Grasshopper [5], have associated libraries, tutorials and forums where a culture of sharing and re-use is actively encouraged. In the design of a simple shape grammar tool, to carry out a few rules to make a hexagonal tiled pattern, made in Processing, the author took code from tutorials, libraries and other users' scripts, and rewrote the code to change certain functions and make a bespoke tool to produce 2D patterns, an example pattern generated by this tool can be seen in Figure 6-4.
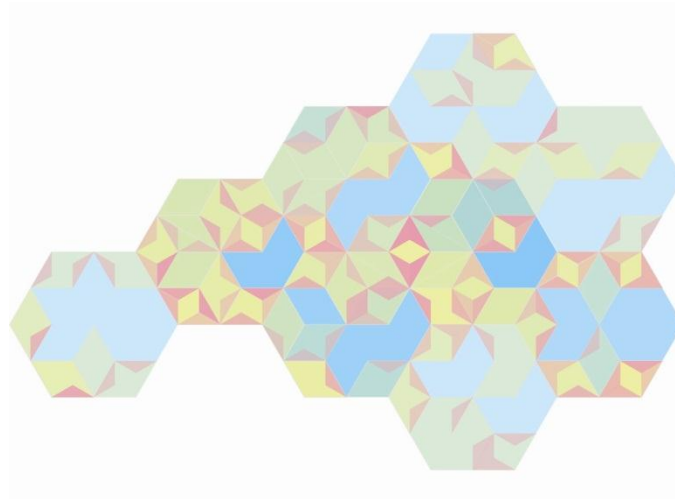
Figure 6-4: Output from a simple shape grammar tool made in Processing by the author

These three design processes exemplify the strategy of accessing the functionality of tools present in a design world and changing these to create new tool functions which can then be used to generate design propositions. This activity meets Boden's [10] criteria for '*higher level*' creativity, that of going beyond exploration and small transformations, to more fundamental transformations of spaces.

6.3   Tool invention

Tool transformations could be viewed on a spectrum, from extrinsic variable transformations, to small functional transformations to fundamental functional transformations that constitute the invention of a completely new tool. Aligning this with the exploration and transformation of rules in conceptual spaces, in the manner of Boden, gives the broad sense that more dramatic tool transformations may lead to higher level creative episodes.

An example of a designer-maker inventing a new and original tool to make work cropped up in the interviews. Kathryn Hinton transformed the functions of tools her tools, by blending the functions of physical and digital tool into a new tool with a new functionality and in the process creating a unique design world, or conceptual space, she terms '*digital silversmithing*'. She developed a digital silversmithing hammer, a haptic tool which looked like a hammer but contained accelerometers to relay movements via a USB port to a piece of mesh modelling software called Z Brush. One of the first digital pieces she made this way was a bowl, which was 3D printed and cast into silver can be seen in Figure 6-5.

Hinton said in her interview that she had to actually learn how to use the hammer as the movements required for successful work were quite different and '*less controllable*' from her usual traditional silversmithing stake and hammer, signifying the tool had opened up a new design world with a new associated structure of tacit knowledge. Hinton had to explore the possibilities and solve the problems of the new design world she had created, such as fabrication challenges and working with the facetted digital aesthetic the pieces have. Ultimately Hinton's creative aim, to produce new pieces of silverware that would not be possible to make with traditional hand silversmithing techniques, was achieved.
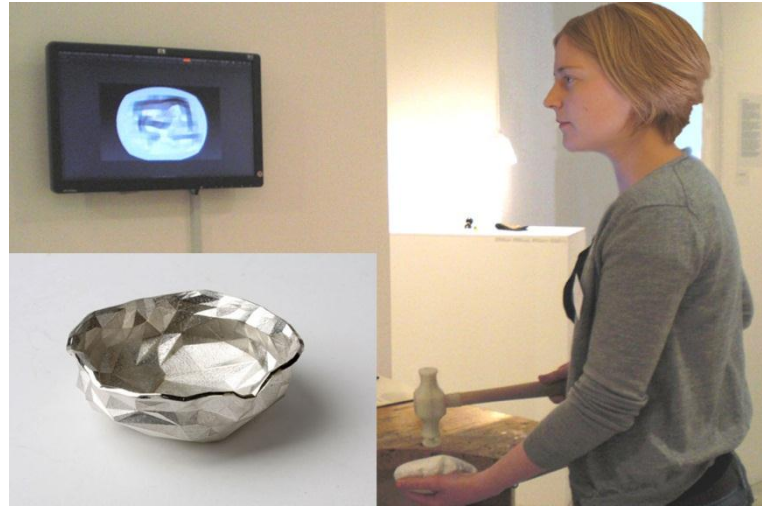
Figure 6-5: Kathryn Hinton demonstrating digital silversmithing and a resulting bowl, 2010

Anton Alverez is an example of a designer who made tools that are even more of a departure from known tools. Alvarez's background is in cabinet making and during his MA in the Design Products department of the RCA he began experimenting with ways of joining materials, happening on some thread on the studio [67]. On discovering the process of thread wrapping he decided he needed a tool to do this effectively and built his thread wrapping machine. The tool spins glue soaked thread around pieces of wood as the user moves them through the machine, see Figure 6-6. Furniture produced using this tool can be seen in Figure 6-7. Like Hinton, Alverez has created a personal design world with new opportunities for exploration through the creation of a new tool, indeed Alverez claims his design process as a '*new craft*' [4]. From observation, the tool draws on known tools such as fibre spinning machines, but the reformat is so drastic it adheres to Boden's highest level of creativity – the building of exceptionally new conceptual spaces.

Figure 6-6: Thread Wrapping Machine, Anton Alverez, 2012

Figure 6-7: Furniture made with Thread Wrapping Machine, Anoton Alverez 2012

The invention of tools by designer makers are creative episodes in themselves, and is likely to lead to design processes that produce highly original and possibly creative outcomes.

6.4   The mechanisms of tool transformation and invention

From the interviews and supporting literature it has become clear that astute selection, transformation and invention of tools is a crucial part of designer-maker design activities, and plays a significant role in opportunities for creative episodes.

The occurrence of creative ideas is often characterised as a sudden mental leap by a designer in creativity and design literature [10,25,29] also offers descriptions of cognitive mechanisms

that facilitate these leaps. These are now discussed and examined from the perspective of tool use by designer-makers.

6.4.1   Tools and analogy

The use of analogies is often posited as the mechanism that yields new ideas [10,19]. Boden in particular emphasises this as the primary mechanism to facilitate the transformation of conceptual spaces. A point of correspondence is discovered between two concepts allowing a new way of perceiving or extending a conceptual space. Sennet [96] suggests a similar remapping of craft techniques can occur, exemplifying the transfer of weaving techniques into the mortise and tendon joints of ancient Greek woodworking, originated by associating lines of thread with beams of wood. From the designer-maker interviews it was found that analogies involving the tools themselves were used by designer-makers.

When developing her digital silversmithing hammer Kathryn Hinton used analogy to develop the concept, this was revealed by her language when she talked about how she came up with the idea for the tool. When describing the new tool she used several similes, '*like a hammer….like a (Nintendo) Wii…like a Wacom pad',* the link coming through the idea of digitally catching the movement of her making actions, mapping the haptic use of a hammer with that of tools used for haptic inputs for computers, merging these tools to create her own distinct new tool.

Rivka Oxman [83] suggests in her research on prior knowledge in design that designers bring in known '*design prototypes*' and try to use and transform these concepts to meet higher level design goals, often through cognitive metaphorical matching. If we take tools in the place of '*design prototypes*', the author's reasoning for using the visualisation tool Jenn3D was to meet a higher level goal of the design project and was based on a type of analogical pattern match: the visual appearance of the Cayley graphs strongly resemble bubble and foam structures, the author was interested in this as the overall concept of the project was to mimic generative structure in nature to make individualised pieces of jewellery. It follows that understanding and

knowledge of tools is used as a '*design prototype*' and aspects of these can be used in the analogical match process to generate new design concepts.

6.4.2   Tools and concept blending

Fauconnier and Turner [35] have developed a more nuanced theory of how two concepts can be brought together to form new ones, this also occurs through finding points of correspondence but produces a third blended space which inherits aspects of the input spaces and has an emergent structure of its own. Taura et al. [111] looked at this idea in the context of design spaces, looking at how designers blended objects and their associated design spaces with others to devise new objects, they found that the more dissimilar the two objects the harder they were to blend, requiring more abstracted concepts to be used, however the result of this were outcomes that were regarded to be more creative than would be seen in the blending of two more similar objects.

Eleanor Bolton's development of her new making technique could be an example of concept or design space blending, creating a new blended making technique which in turn produced new artefacts, rather than just a third artefact as in Taura et al. [111]. Bolton stated that she had in mind the concept of 'chains' an archetype of jewellery design but had also selected, rope, and a needle and thread as her materials and tools. She described that her new making technique inherited the look and idea of linking and continuity from the 'chain' and inherited the method of stitching from textiles via the chosen materials.

This example shows that concept blending is used by designer-makers, in addition and building on the ideas of Taura et al. [111] is that the input can not only be a design artefact but actually be tools and associated materials and processes that in turn produce a new design. The output of such a blend in this case was not a single novel design artefact but a new making process or 'tool', for the purposes of this research Bolton's making technique could be viewed as a tool as it takes in material and transforms it according to a set of rules or mechanisms.

6.4.3   Tools and emergence

Emergence, explicating formerly implicit properties of a domain [37], is used frequently in design, creativity and making literature. Making use of unexpected emergent properties can produce creative ideas, Dorst and Cross [29] found that the designers in their study on creativity seized on a new piece of information they were given during the design process and then often used it to make the creative '*bridge*' between their problem and solution spaces. Schön [94] also found designers to be consciously searching for and using emergent properties within their sketches to form creative ideas. Adding to this Rivka Oxman [84] found that good domain knowledge was required for the recognition of useful emergent features in this sketching process. Ingold's [50] anthropological viewpoint is that what is made emerges from a material milieu in flux, and the maker coaxes and observes useful structures over time.

Making use of the emergent properties of tools was found in the interviews with designers. Eleanor Bolton's blending of concepts provided a new making technique whereby rope was stitched together in coils to create long flexible tubes, finished into loops to make necklaces and bangles. The technique exhibited emergent properties that Bolton had not initially anticipated but then began to put to use to develop further designs: '*so it just started off that I was making these tubes….then using the idea that like in knitting and crochet you add and drop stitches to create different shapes and forms*'.

By increasing or decreasing the stiches on successive coils, similar to a technique used in circular knitting, the overall circumference of the tubes could be increased and decreased, giving an opportunity to experiment with different shapes in the designs, as in the pieces shown in Figure 6-8. This was an emergent tool capacity Bolton recognised in the tool she was using found through knowledge of another tool technique.

Figure 6-8: Rope necklaces with varied forms, Eleanor Bolton, 2010

Ceramics designer Ian McIntyre described how he purposefully searches for emergent properties in his experimentation with tools and materials. In his interview he stated that in his MA project: '*the idea was to elevate the quality of the material and elevate the process as well, so it was about finding a quality that only could be produced on the jigger-jolly machine and a quality that could only be produced in clay*'. The emergent property that McIntyre eventually made use of was the individual and uneven edge that appeared when a plate, bowl or cup is made on a jigger-jolly machine with slightly too little clay, this can be seen on the plates in Figure 6-9. Typically the clay would extend the edge of mould and then be trimmed off to give a smooth, uniform finish to the plate, however McIntyre saw value in keeping the untrimmed edge, as it gave individual character to an object produced with a mass production process. Another benefit was that this approach removed a step out of the production process and making it more time efficient.

Figure 6-9: MA project plates, Ian McIntyre, 2010

Rivka Oxman suggests that good domain knowledge is required to see and use emergent features. It seems from these examples that a close knowledge and personal use of tools helped the designers find emergent features that they could then capitalise on.

Although in depth knowledge of tools can aid creative ideas, too much expertise may also hamper creativity at times. Experts can face 'designer burnout' [34] and fixation [103] which can cause lapses in the production of creative solutions for some experienced designers. The idea of designer experience of tools and materials being to the detriment of creativity cropped up in the interview with McIntyre: '*a lot of my original projects were successful because I didn't know the rules… it's a double edged sword because now I know the material too well so I rule out all of the experimentation that could possibly yield new ideas…which is why the next project I do probably needs to be outside of ceramics, to freshen me up a bit*'.

Figure 6-10: Slush cast bowl, process and finished bowl, by Ian MCIntyre, 2008

Emergence of serendipitous outcomes is not always born of expertise. A particular example of this was described by McIntyre, as a novice designer he made a severe error in the design of an expensive mould he couldn't afford to re-make and was forced to rethink his whole design and production process. He had planned to pour molten pewter into the mould and flip it upside down to create a drip effect, however he had overlooked that there was nothing to stop everything falling out of the mould and destroying the pieces. Eventually through experimentation he found a new way of coating the mould by swirling it around the sides the right way up, this process can be seen in Figure 6-10 alongside one of the finished vessels. The outcome was a series of bowls that proved to be one of his most popular products, even

being commissioned as a gift by the government to give world leaders at a G20 summit in London.

6.5   An exception

The interviews undertaken sought to look at the use of tools in the designer-makers' processes and how these corresponded with established literature on creativity. The interviews revealed that tools play a vital part in the creative episodes of designer-makers.

One of the designers interviewed, Marina Brown, despite working closely with digital tools and making the finished objects herself, has a distinctly different working environment from the other designers interviewed. Her work is carried out as part of a team, focussed on corporate clients and has tightly restricted design briefs. Accordingly her descriptions and her use of tools was different from the designer-makers. Brown described how she almost wanted not to notice her tools; they were a means to an end. She described how moving between different computer set ups was a big downside of the freelance work she often did, as she had to re-tune things such as keyboard shortcuts to work efficiently, an example that if attention was paid to the tools it was because they were causing problems for her work flow. Attempts at creative design solutions occurred in the stages before the making of the adverts, clients and design teams would work on the design concepts verbally and with story boards, the making process was not seen as a place to be creative in a significant way.

Another main reason behind the lack of tool experimentation or related creative ideas also was related to Brown's working environment, as freelancer in large corporate structures there seemed to be more focus on time and cost than creativity generally, not just relating to tools. She described how creative ideas suggested in early design meetings were often lost in the finished adverts as they were altered by different opinions in creative teams or diluted by clients, as well as the pressures of time and cost.

The interview with Marina Brown reveals that not all types of design uses tools to stimulate creative design. On-line advertising has different goals from disciplines like ceramics and jewellery, and perhaps the more abstract or narrative based the design world becomes the less likely tools are to be significant part of creative episodes.

7 THE TOOLS ARE THE RULES – USING SHAPE GRAMMAR TO DESCRIBE MAKING PROCESSES

The interviews with designer-makers provided an overview and confirmation of the ways tools can be used to stimulate creative episodes and the mechanisms through which these can occur. The descriptions of the designer-makers matched a variety of established literature on creative activities, but brought the specific discovery that tools are a conduit for these activities.

Formalising some of these practices into coherent strategies could be useful for designer-makers and other designers seeking to be creative with tools and shape grammar could be a useful framework for doing this. Shape grammar is a rule based theory and rules are a concept used to explain creative activities, particularly by Boden [10] and also feature in Dormer's explanation of craft learning [27]. Shape grammar is based on visual calculations, manipulating and transforming shapes, rather than trying to use language to define design activities. Recently Knight & Stiny have suggested that the sketching and seeing of shapes and the doing and sensing of materials [65], in other words making, a process that often defies verbal descriptions [27], is very similar. More specifically than Knight and Stiny and others this thesis proposes that tools can be characterised as transformational rules, and that this is the key to developing formal descriptions of making processes and creative episodes in making.

Of particular use are shape grammar rule schemas, Stiny proposes the use of these as a more appropriate way of describing what designers and artists see and do in general terms, these are now discussed as a way of representing designer-maker activities.

7.1   Shape grammar rule schemas

Shape grammar rule schemas are more general descriptions of the kinds of operations used in shape grammar. In his 2011 paper '*What rule(s) should I use?*' [109] Stiny sets out a taxonomy of schemas and shows their relationship in a lattice, which can be seen in Figure 7-1, at the top is the most general definitions, moving downwards the rule schemas become further categorised.
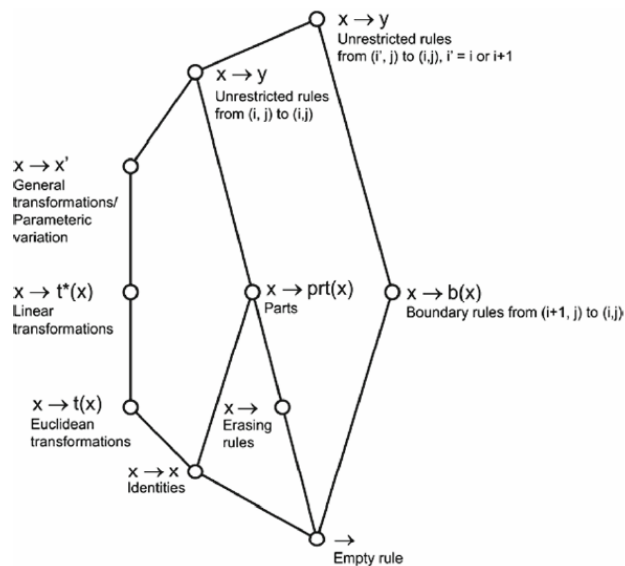
Figure 7-1: Stiny's lattice of rule schemas

Some of these were summarised in the literature review, in section 2.3.2. Modelling tool activities by aligning them with these schemas could be a way of creating a formal framework of useful definitions to support creative making. The following sections look at Stiny's schemas in more detail and compares them with designer-maker activities to examine if they would be appropriate.

7.1.1   Addition schema

It was seen from the analysis of the interviews with designer-makers that they used shared and personal design worlds as a basis for their design activities and that tools played a key role in defining these design worlds.

Initial tool and material selection could be seen as a process of selective addition to a design world. Addition rules feature in shape grammar, at the start and during a shape grammar design process. Addition rules add shapes onto the page, an example of a shape grammar addition rule that adds a square in a blank space can be seen in Figure 7-2.
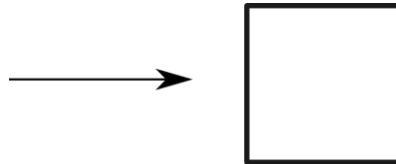
Figure 7-2: Example of a Shape Grammar Addition Rule I

Stiny uses notation to represent the rule schemas. For an additive rule like the one in Figure 7-2 the notation is:

$$\rightarrow x$$

Stiny [109] describes this as representing the process of adding design elements to a design process, these are taken from existing art and design. Indeed the designer-makers were seen to reference designs and tools and add them to their personal design worlds during each design process. In terms of tools we saw that tool selection and addition to a design world was a crucial part of the designer-makers work. Designers-makers were adding tools to their design worlds, which could look like this:

$$\rightarrow t(x)$$

This is a schema which Stiny does not extrapolate his notation to include, perhaps Stiny considers the addition or selection of rules is obvious and flexible, however the interviews revealed that selecting, applying and transforming tools is central to their design activities, so a less ephemeral approach to actual rules/tools is essential to model designer-maker protocols.

Another kind of addition shape rule is one which adds a shape with reference to another shape already present in a design, like the rule shown in Figure 7-3 and therefore defines some kind of spatial relationship between two shapes.
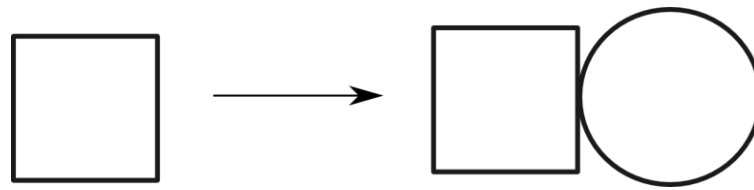
Figure 7-3: Example of a Shape Grammar Addition Rule II

Stiny's schema notation defines such a rule in the form:

$$x \rightarrow x + y$$

This represents the process of combining design concepts, used by designers to generate new design solutions. For the designer-maker juxtaposing of pieces of material in designer-maker practice is important, and tools usually perform these actions. For example the woodworker may select and join pieces of wood in particular ways as he or she constructs a piece of furniture. When and where to apply tools to achieve various material transformations is similar to the application of rules on particular shapes, and requires designerly judgement.

Apparently simple additive actions can be used cumulatively to build large, complex entities. Stiny exemplifies this by demonstrating that patterns generated in cellular automata can also be generated with shape rules [108]. Cellular automata show that a few additive rules used recursively can generate numerous patterns many with higher level emergent features. The same happens in making practices, knitting in particular demonstrates similar characteristics, a small number of different stitch types applied recursively in different order can produce an unlimited number a of pieces of fabric with different sizes, shapes and textures without changing any other variables. Similarly Knight [55] suggested new design languages could be found by changing where and when rules were applied by using and changing state labels in design generation using shape rules.

Tools are entities in their own right in designer-maker practice and so could be subjected to the same schema, tools can be added, combined and juxtaposed, as interviewed designer Kaur's Chai Tea Strainer demonstrated.

Expanding Stiny's notation to subject rules and tools to the addition schema we get:

$$t(x) \rightarrow t(x) + u(x)$$

Where u represents a new tool that can transform entity x is added to the design process.

Designer-makers subject materials to a series of transformations, arbitrated by tools. It was demonstrated in the previous section that designer-makers can use tools in new combinations to stimulate creative design. Tools can actually be sets of sub-tools combined together in hierarchies; a series of transformations which can be seen as an over-arching transformation. For example Eleanor Bolton's stitching technique could be viewed as a tool, comprised of a subset of transformations applied by needle and hands.

7.1.2 Boolean operations

Addition rules can place shapes in spatial relationships with one another like in the rule in Figure 7-3. Shape grammar shape calculations adhere to Boolean operations, so in cases like these the shape on the right hand side of the rule is a homogenised new single shape.
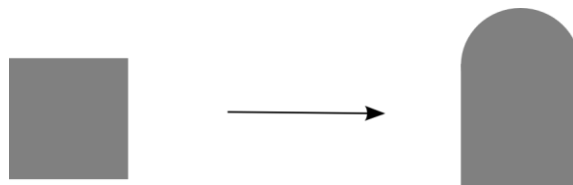
Figure 7-4: Addition rule demonstrating Boolean addition

Some materials can be made to, in effect, combine in a similar way, for example pieces of wet clay may be joined and smoothed over, so like in the Boolean addition the pieces of wet clay become merged with one another without a boundary, the original shapes subsumed. It could be said that two pieces of material of the same kind are more likely to behave in such a way.

More often than not the addition of two pieces of material together is likely to give far more complex results. A spectrum of levels of integration exists when a maker attempts to combine two material objects. Shape grammar does address this to an extent with the idea of labels and weights, which is discussed later in this section.

To focus on tools, combining tools can give new tools that sit on a spectrum of how integrated the new tools is which may or may not have bearing on how different the transformations it can make with that of the transformations of the original tool.

Jasleen Kaur's Chai Tea Dispenser was made from joining other readymade tools to then, in turn, perform another transformation – on the tea. Kaur added ready made tools; they were cleverly and elegantly subsumed into a greater tool but not fully homogeneously integrated into one. When asked about refining her designs Kaur explained that she enjoyed the informal and humorous aesthetics of the ad-hoc. In theory, once working Kaur could have produced a more homogeneous version of the tool, however tools are always likely to exist as combined parts.

Katherine Hinton's digital silversmithing hammer has a more refined appearance, again it is built from parts that Hinton either procured (electronics) or made (shaft and head), but is more integrated as a tool. Perhaps this is because Hinton performed her tool additions at a higher conceptual level, taking certain conceptual elements from hammers, graphics tablets and Wii controllers, these concepts were well integrated before the production of the actual physical tool.

It seems, like in shape grammar, the nature of the materials or tools to be combined must have in common some kind of homogeneous property if the designer desires a high level of integration in the output. However, it has been seen from the designer-makers interviewed that the level of integration does not necessarily affect the quality of the tool for design produced, it may still be more than suitable as a solution.

7.1.3 Parametric schema

Transformation schemas are part of Stiny's most general schema for shape operations, which he notates as:

$$x \rightarrow y$$

This schema states that a shape has been transformed in any way and this could be equated with transformations made on material by a tool in designer-maker practice. To expand this style of notation:

$$t(x) \rightarrow u(x)$$

As can be seen in Stiny's lattice of shape grammar schemas, in Figure 7-1 this schema contains nested sub-sets of schemas. The next highest level of schema for shape transformations is:

$$x \rightarrow x'$$

Described by Stiny as parametric transformations, the implication is that the transformed shape on the right hand side still shares some commonality with that on the left hand side.

In making terms a parametric transformation of a piece of material could be seen as giving an output is still comprise of the same molecules and atoms, but changed in some way, be it a change of shape or size, or a more physically complex change like a state change from liquid to solid.

The interviews revealed that designer makers routinely make transformations to the tools they are using to achieve transformations they require. When it comes to tools parametric transformations are common and could be notated:

$$t(x) \rightarrow t(x)'$$

Examples of this were seen in the interviews with the designer-makers, they changed parameters in their tools to in turn produce different material transformations, described as tool transformations that changed tool variables but not intrinsic functionality.

Kathryn Hinton described the common practice of changing the shapes of hammers and stakes to achieve different hammering effects and final forms. This could be graphically visualised in the style of rules as in Figure 7-5, the material is subject to the blow of a flat hammer, giving a flat impression, the parametric shape change of the hammer head shape gives a new rounded impression.
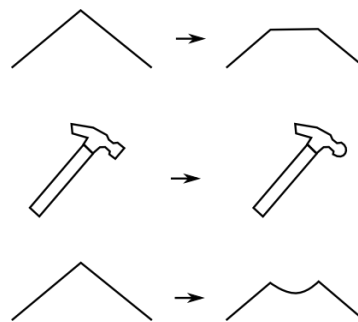
Figure 7-5: Parametric transformation of a tool

Eleanor Bolton also changed the parameters in her tool, the technique of coiling and stitching rope, she varied the number of stitches in each coil resulting in different thicknesses in the coils to play with the overall forms of necklaces. Jasleen Kaur re-parameterised the Tala Cook's measure, reformatting the measurement system produce new specific recipes.

Tools are transformed by other tools to generate new designs, or in terms of shape grammar rules are transformed by rules to generate new shapes.

7.1.4   Identity schema

Stiny includes a schema in his taxonomy that deals with shape identity, notated as:

$$x \rightarrow x$$

This schema is used as a way of changing the identity of a shape while the shape itself is unchanged.

This obviously takes place with bits of material; they can be interpreted and reinterpreted in a myriad of ways, like shapes. Lumps of clay are also sculpted animals; planed pieces of wood are surfaces for tables or shelves. The 'tool' for such operations is predominantly the eye, armed with higher level concepts and knowledge to allow various interpretations of objects. Dormer highlights the importance of connoisseurship as a craft skill [27]; the honed ability to identify certain qualities in a crafted object, there but not always noticed by the untrained eye.

The designer makers were also carrying out such operations on tools, they gave tools new identities to use them in different ways, without actually altering the tools themselves. The author in effect changed the identity of the Jenn 3D software programme. The actual programme was not altered in anyway but assumed a new identity in the world of jewellery design. So again this schema can be expanded to operate on tools and rules:

$$t(x) \rightarrow t(y)$$

In this case x and y representing the same tool, t, operating in different contexts, a description of a creative activity where a tool is used in a new and unusual way by a designer-maker.

7.1.5   Selection schema

A super-set of the identity schema is the schema which picks out parts of shapes:

$$x \rightarrow prt(x)$$

This schema is used to pick out a part of a shape most likely with the intention of performing a further transformation. This is a process of selection of design elements in order to put them to new uses.

Designer-makers may pick out parts of the designs they are making for closer attention. As was seen in the analysis of the interviews the designers were often looking for emergent features while they were transforming materials in the hope of finding a new useful quality that could then be used to seed a creative outcome.

What this schema can represent, as suggested by Stiny [109] in his paper on schemas, is that picking parts of designs is representative of creative cognitive processes in art and design generally. Creative ideas often occur by taking parts of other pieces of existing art and design and recombining into something new; he states that copying is not cheating, but a natural process of creative process. It also concurs with Boden's [10] ideas on combining concepts through analogy and creative methods like concept blending [111]. For designers like Hinton and Bolton this part taking occurred at a conceptual level, however was still done with a focus on tools. Therefore if we interpret this schema and notation into a transformation on a tool we get:

$$t(x) \; \rightarrow \; prt(t(x))$$

This can model the creative activity of isolating parts or functions of tools with the intention of recombining them into new tools.

7.1.6   Boundary schema

Similar to the schemas that define identification and parts is the schema that picks out the boundaries of shapes:

$$x \rightarrow b(x)$$

Taking into account rules such as the one seen in Figure 7-6, where a solid square is transformed to the square boundary.
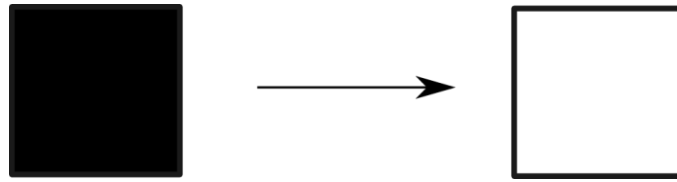
Figure 7-6: Boundary shape rule

When shape outlines are isolated, dimension of the shape is hierarchically decreased, in this case from a plane, a higher dimensional object, to lines of lower dimension. In terms of tools this could be akin to using a guide or jig, such as a ruler to draw a straight line, a boundary is left behind.

Stiny also discusses the inverse of some of his schemas, in the case of the boundary schema inverse:

$$x \rightarrow b^{-1}(x)$$

He likens this to the procedure of shading within a shape boundary and then erasing the boundary, the visual effect being reversing the left hand side and the right hand side of the shape grammar rule in Figure 7-6. Again this causes the inverse effect in dimensionality, going from a set of lines to a plane.

Such a procedure has much in common with the use of moulds and other tools which impose new boundaries on pieces of material, which are then removed, leaving the material in a different form from previously.

Like selection schema, discussed in the previous section, boundary schemas could be seen as the activity of moving tool concepts from their physical form into cognitive representations. This was seen as a way by the designer-makers to manipulate tool ideas and then return to the physical realm to produce homogenised, personalised tools which in turn they used to produce their design outcomes. Again to expand the rule schema notation by Stiny it can be suggested that:

$$t(x) \rightarrow b(t(x)) \quad \text{and} \quad t(x) \rightarrow b^{-1}(t(x))$$

could be used a representative definition of this creative tool activity.

7.1.7 Subtraction schema

Stiny also suggests a schema for erasing shapes:

$$x \rightarrow$$

This is the inverse of the addition schema discussed earlier.

The process of taking away a material is a fundamental activity in making. Carving and cutting are examples of producing something by actually removing something.

Several of the designer-makers described that they thought creative ideas were simple and elegant. Ian McIntyre described how he actually looked for processes he could remove from standard production processes to actually add interesting features to the designs. Again this shows that tools as well as materials are subject to subtraction transformations in creative episodes, removal of tool elements can provide desirable restructuring of tools, a deliberate omission can be as pivotal as an addition in the development of a creative episode. To reconfigure this particular schema in terms of tools we can notate:

$$t(x) \rightarrow$$

7.2 Labels and weights

As discussed previously, in shape grammar, shapes adhere to Boolean operations. Stiny [108] acknowledges that these operations are not always desirable for a designer while manipulating shapes. To provide a way of choosing which shapes will adhere to the operations with one another he presents a system of labelling. This means shapes with different labels will not interact with one another in transformations and are effectively separate, as if on different

layers; transformations with labelled shapes can act on labelled or unlabelled shapes, while avoiding Boolean interactions.

Physical materials interact in a wide range of ways when they come into contact with one another. Some may mimic Boolean interactions, as mentioned liquids or wet clay may be subsumed into one piece, any boundaries lost. Other pieces of materials may behave as if they are labelled, not joining as they come into contact and unable to occupy the same space.

Weighted shapes are an extension of labelling, where Stiny [108,106] suggests that weights represent material properties and can be associated with shapes. Weights also adhere to Boolean operations; a full description of weights can be found in Part II of this thesis, in section 9. A significant difference between Stiny's weights system and real material properties appears to be that weights are attached to shapes, but do not have influence on the shape of the shapes, however in the physical world material properties can have a significant influence over the shape and form of an object under tool transformation.

Shape grammar, in particular rule schemas, seem well suited for modelling designer-maker activities involving tools. Rules are a concise way that may prove useful to formalise strategies for creative design. However, modelling the complex relationships of material interactions and properties in a making process is an additional task. Part 2 of this thesis looks at weights and their use as a method of generating designs for multi-property 3D printing systems and how this can support creative computational making, through design experiments the way certain properties can be modelled by shape grammar weights is investigated, bringing new insights for shape grammar weights and making.

7.3 Shape schema grammars

Woodbury [113] proposed another way of characterising flexible rules, rather that rules being schemas it is suggested that shapes could be schematic. Rules can be applied to any shape instance that meets given constraints and transform them to new parametric sets of shapes.

Woodbury et al. viewed this as an approach to using shape grammar in a computational context, finding that it became a constraint solving computational problem and explored some of the complex issue surrounding the possible computational application.

However taking the concept of parameterised shape instances and applying it to designer-maker tool use could be useful. Tools extend but restrict our actions [77] on materials, each tool has related material instances where it could be used, transforming material into a wide array of possible material instances. It may also be a way of addressing the effects of material properties in making processes that can have an effect on the way material is transformed, in reality this is often a more complex process than using weights reflects.

8 ANALYSIS OF A DESIGNER-MAKER DESIGN PROCESS WITH SHAPE GRAMMAR SCHEMA

Comparing shape grammar schemas to making practices has found that there is much in common between the two. To try confirm and discover more about the potential of using similar schemas to describe designer-maker processes a designer-maker process of the author's has been modelled in more detail, with particular attention to how tools were selected, applied and transformed in terms of these kinds of schemas.

The design process selected was performed by the author in parallel with the first year or so of the research culminating in this thesis. At the time the design process was independent of the research and was not intended to feature as part of it, but part of the author's personal design practice. It is hoped that by using first-hand design experience the author can attain a deeper level of insight into how and why things unfolded throughout the design process. Unfortunately as it wasn't intended to be part of the research detailed notes or journaling were not carried out at the time and the modelling has been done from memory of the events. The nature of the modelling is focussed on the actual procedures concerning tools, rather than cognitive processing, so is less likely to be affected by memory factors or post rationalisation. The other advantage of this situation is that the author, in the role of designer at the time, was not influenced by trying to prove or disprove any hypotheses or aware of the outcomes of other facets of this research, such as the interviews at the time.

8.1 Tool selection – addition schemas

The case study used to illustrate the model is a design process carried out by the author as part of her designer-maker jewellery practice. The design process was initially motivated by a competition brief provided by the Goldsmiths' Craft and Design Council as part of their annual competition.

The brief was in the category of '*Production Jewellery*' and asked the designer to design a piece of jewellery incorporating wire that was easily repeatable in small numbers using production processes and tools such as jigs and casting.

The brief added categories of tools and materials into the design world of the designer. Similar to the cases of the other designer-makers, tools and materials were a key part of the design world, and primary generators [25] for the design process. More specific tool selection occurred beyond this with the designer selecting the CAD program Rhino with its accompanying graphical algorithm editor Grasshopper, familiar to the designer, alongside SLS (Selective Laser Sintered) nylon 3D printing techniques the author hadn't previously used as a means of production. This tool selection activity composed a design world of tools and related design elements that were developed to generate design outcomes to answer the brief in an original way. In terms of tool schemas this can be modelled with the notation of an addition rule:

$$\rightarrow t(x).$$

8.2   Inspiration – parts schemas

Some time was spent mulling over the brief until inspiration came in the form of an object designed by Michael Cornelissen, *36 Pencil Bowl*. This is a 3D printed base in which pencils can be slotted in to form the sides of the bowl, and can be seen in Figure 8-1.

Figure 8-1: 36 Pencil Bowl by Michael Cornelissen, 2010

The designer took a part of this design, the idea of slotting cylindrical objects into holders to be adapted into her own design for the brief. This process resonates with Stiny's shape grammar schemas for design, where he suggests that parts of design elements, in this case an existing design, are picked out and used in further design transformations, represented by the rule notation, $x \rightarrow prt(x)$. This particular creative episode, although not involving tools, occurred through recognition of corresponding elements – pencils and wires, to provide a solution for the design process on how to combine the digital tools of the author's personal design world with the traditional material from the brief, of precious metal wire. This shows that although tools feature heavily in designer-maker's reasoning and creative episodes, they also may use other sources for these.

8.3   Tool making

The designer then went onto a process of making computational Grasshopper tools to construct visually representational geometric forms in Rhino3D, lines represented wires to explore the possibilities of different forms for the jewellery.

The transformations these tools perform were parametric manipulations of digital representations of potential material structure. Grasshopper is comprised of tools that perform the modelling commands available in Rhino that can be joined up to create algorithmic form generators. These tools perform operations on the input data, and are represented graphically by boxes and can be joined together in flow chart style.
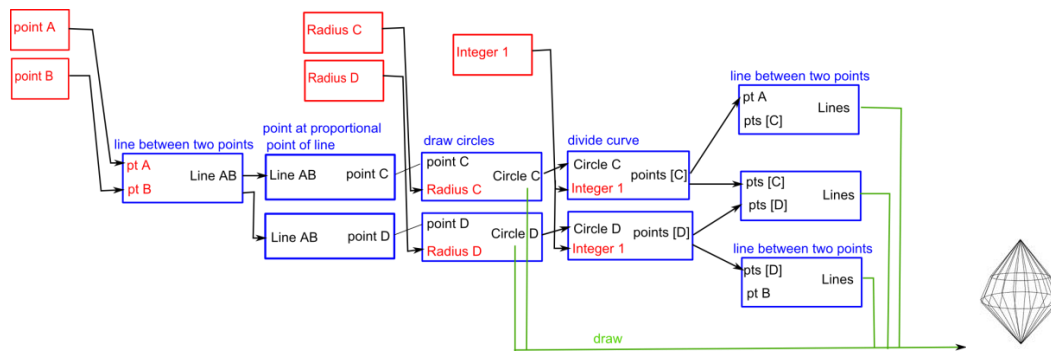
Figure 8-2: Diagram of Grasshopper tool in case study

The first version of the tool made by the designer took two points, between which it found a point and used this as the centre of a circle. The circles are divided a number of times and lines drawn between these points and to the starting points. A schematic drawing, which looks similar, although simplified, as what would appear in the Grasshopper workspace, can be seen in Figure 8-2, red boxes show inputs, blue boxes show transformation and green lines show the chosen outputs to form the design.

The analysis of the interview showed that the combining of pre-existing tools in new ways often gave rise to creative episodes. This also happened in the author's use of Grasshopper in this design process, a set of modular computational tools can be linked in different ways to form higher level tools that perform complex operations. Using shape grammar schema this can be modelled in terms of addition rules of the form, $t(x) \rightarrow t(x) + u(x)$, in this case tools are added and carefully juxtaposed to create new tool combinations or integrations.

8.4   Tool transformation

Dorst and Cross [29] modelled creative design processes as a process of '*co-evolving*' problem and solution. In the designer-makers' design process a similar model emerged in the interviews. Rather than design concepts the designers co-evolved their tools and desired outcomes until an object was produced that they felt was new and valuable in the context of the shared design world they had chosen. Dorst and Cross [29] demonstrated in their study that the designers made their creative '*bridge*' between problem and solution when a new

piece of information appeared to them. Similarly the designer makers searched for something new to them by experimentation with physically with tools and or cognitively with tool concepts until they observed something they felt was useful.

In analysing the author's computational design and making process it became apparent that the author performed many transformations on the Grasshopper computational tool, effectively evolving the tool to drive towards the generation of a suitable design.

8.4.1   Parametric tool transformations

One of Stiny's schemas represents parametric transformations, where the input shape has commonality with the output shape, $x \rightarrow x'$. In this design process the initial form in the design process could be parametrically transformed. An example of a parametric transformation of one of the designs could be visualised in a shape grammar style rule, as shown in Figure 8-3, where a design is transformed by changing the position and radius of the circular parts of the design.
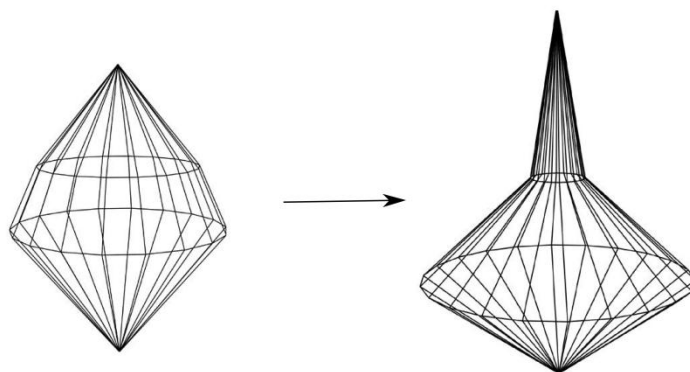
Figure 8-3: Visualisation of parametric shape grammar transformation in case study

The designer wanted to explore other versions of this design, instead of simply taking this first design and transforming it directly the designer returned to the tool, and changed parameters within the tool, something done easily in such a computational digital tool. New design possibilities, structures of lines, could be generated by changing the centre point and radius

parameters in the Grasshopper computational tool. This is another example of rules being used to transform rules, to revisit the expanded version of Stiny's rule schema:

$$t(x) \rightarrow t(x)'$$

Where a rule is transformed parametrically and then in turn applied to the shape or in the case of making, some kind of material, either physical or digital.

The author, like the interviewees, performed parametric transformations of their tools, trying to co-evolve the tool and solution to find a favourable outcome, similar to Dorst and Crosses' [29] 'bridge'. This activity can be described using shape grammar theory, however it offers a new perspective on shape grammar not emphasised before, that designers sometimes focus on honing the rules they use, rather than the shapes.
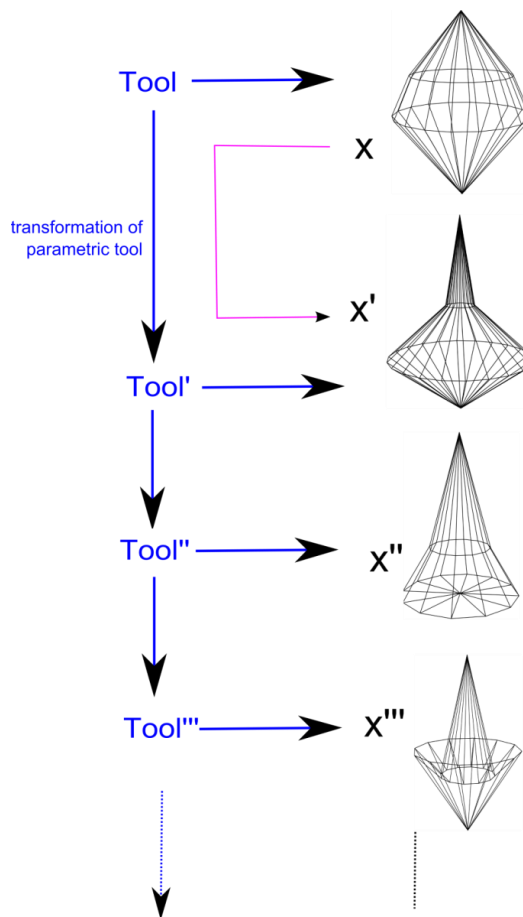
Figure 8-4: Parametric transformation of a computational tool

8.4.2 Functional tool transformations

The designer added and removed certain functionalities in the tool as the design process progressed, diagrammed in Figure 8-5. These transformations used the original tool as a basis but this was then altered to provide different kinds of outcome. The process was experimental, trying out possible variations in the tool to see the aesthetic and functional effects in the designs themselves.

Functionality was added so that the tool would generate the connectors that the wires would slot into, to be 3D printed, and would be updated as the actual basic designs were parametrically explored.

Other functionality additions to the tools were that of being able to twist and tilt the circles in the design, see Figure 8-5. This was purely carried out as an exercise in aesthetic curiosity, to see if the designs from these altered tools were interesting in anyway, in the hope that some a creative discovery might be made. This particular experiment turned out to be a dead end and this functionality was effectively removed from the tool and a new path was taken. Knowledge gained from successful or semi-successful designs from each functionally transformed tool feedback into the next tool transformation.

Again this activity was discovered in the interviews and was echoed in Stiny's design rule schemas, however in terms of tools the new notation offered is $t(x) \rightarrow u(x)$, this signifies that the tool has had substantial changes made to it and has a diiferent identifier, u, in this case.

This process of adjusting tools has some correspondence with Schön & Wiggins' [94] '*see-move-see*' designer protocols, the actions of appraising design representation, making a change to it and then appraising the new representation. This case study reveals that the '*move*' action can be more than a change on the design representation, but a transformation situated on the tool or rules that in turn generate the new design representation. Eventually the tool was transformed in less experimental ways to specifically hone it to produce Rhino models that met the physical and material specifications, ready for the 3D printing process.

The earrings shown in Figure 8-6 were a final design outcome from the computational making process, the grey parts were 3D printed in a SLS nylon/Aluminium powder mix and then a process of hand construction and gluing of the silver wires in place finished the pieces. They were submitted to the competition and won a silver award in the production jewellery category and an additional silver award for technological innovation, Figure 8-6 shows a section of a page of the awards catalogue with an image of the earrings and listing of the technological innovation awards that year.
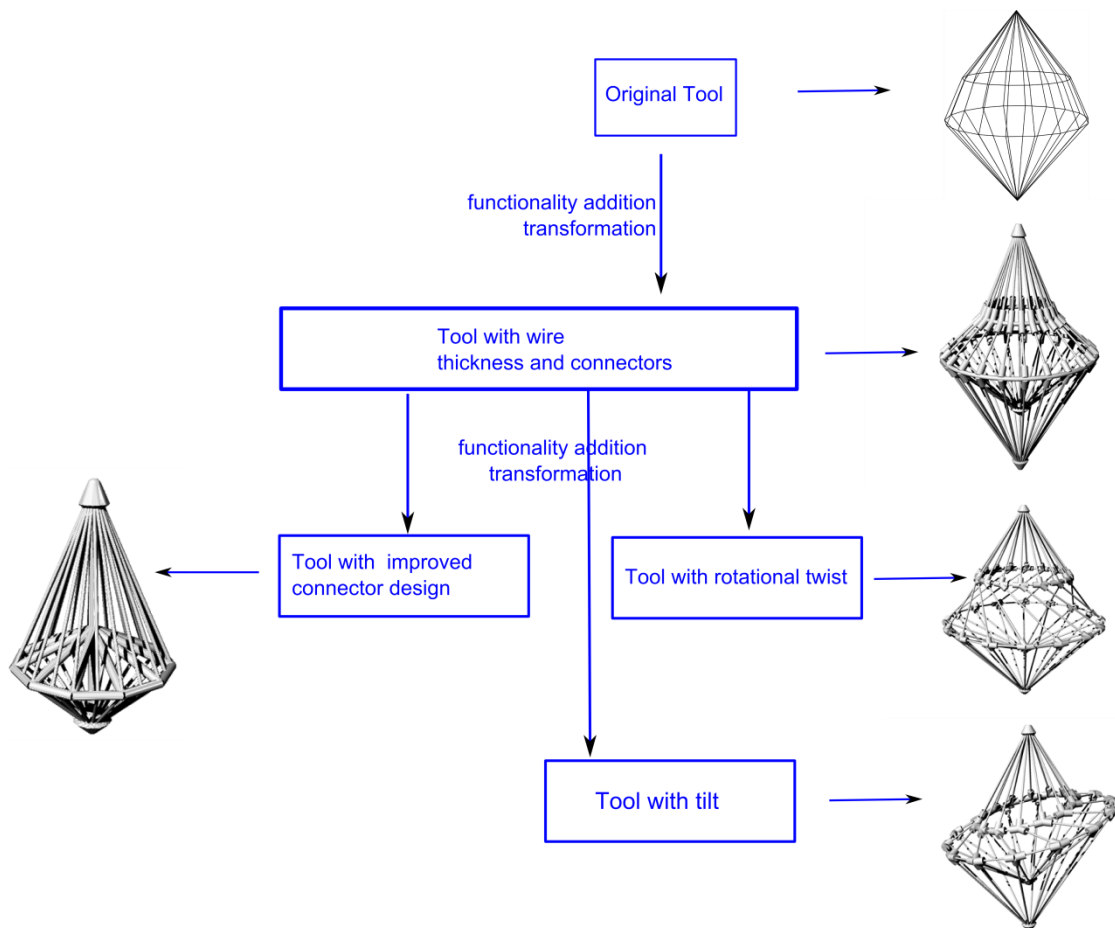
Figure 8-5: Diagram of functional transformations made on a tool in case study

Figure 8-6: Section of page from Goldsmiths' Craft and Design Council Awards catalogue 2012

Again in this design process the emphasis of activities was on developing and transforming the tool to give new designs, rather than transforming the designs themselves. This is where designer-maker protocols and shape grammar have different active focusses, shape grammar focuses on transforming shapes, where designer makers focus on transforming and honing their tools and this activity is often where creative discoveries are made.

8.4.3 Tool reformatting

Although the design outcome of the design process so far had been somewhat successful, as judged by an expert body, it was known by the author that as a product the design had serious flaws in how it had to be fabricated. The actual hand construction process with the 3D printed part and the wires had been a lot more time consuming and awkward than expected and the 3D printed material, an aluminium dust and polyamide composite, selected for its aesthetic qualities was prone to breaking at the sizes required for the pieces.

At this point the designer decided to continue developing the designs, but with the competition passed more freedom was available to co-evolve the desired solutions. The designer decided to remove the stipulation for metal wires in the piece and concentrate developing homogeneous pieces, printed as one part, much like a Boolean shape operation on the design. This gave the benefit of cheaper, lighter, more durable pieces and more efficient

production, the transformation of the pieces in shown in a shape grammar style rule in Figure 8-7.
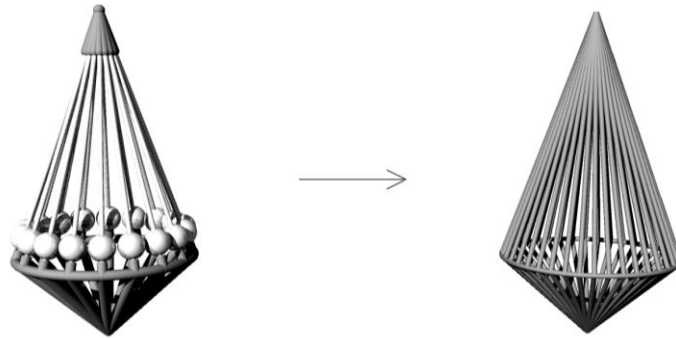
Figure 8-7: Transformation of the design

The author returned to the Grasshopper tool, performing subtractive transformations to the tool, removing functionality relating to the separate metal and printed parts. In this case there was a design transformation that in turn informed transformation made on the tool, an inverse procedure from what was previously documented in this computational making process.

While returning to a more streamlined tool a discovery crucial to the new design process was made, the author perceived the emergence of Moiré patterns on screen as the number of lines or 'wires' was increased, as can be seen in Figure 8-8. This was the most significant creative episode in the design process, and occurred through emergence from tool selection, combining and transformation. The designer had noticed this phenomena previously however it hadn't been compatible with using metal wires as the competition brief required due to weight and scale considerations, but could now focus on developing this discovery into an important design feature.
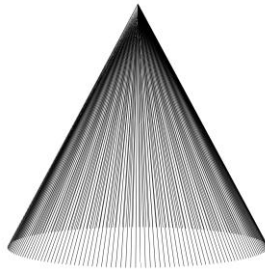
Figure 8-8: Moiré patterns appearing from large numbers of lines as generated by the Grasshopper tool

Again the tool was transformed to explore the numbers of wires, thicknesses and sizes of possible designs to give the best visual effects while meeting the requirements of the 3D printing processes, screenshot is shown in Figure 8-9.

Following this the designer actually stepped away from the Grasshopper tool. It had fulfilled its job as an exploration tool and serendipitously yielded a creative episode through exhibiting emergent features that the designer was able to perceive and make use of, conforming to the idea that creativity can come about through the harnessing of emergent tool features, supported in creativity and design literature [10,29] .
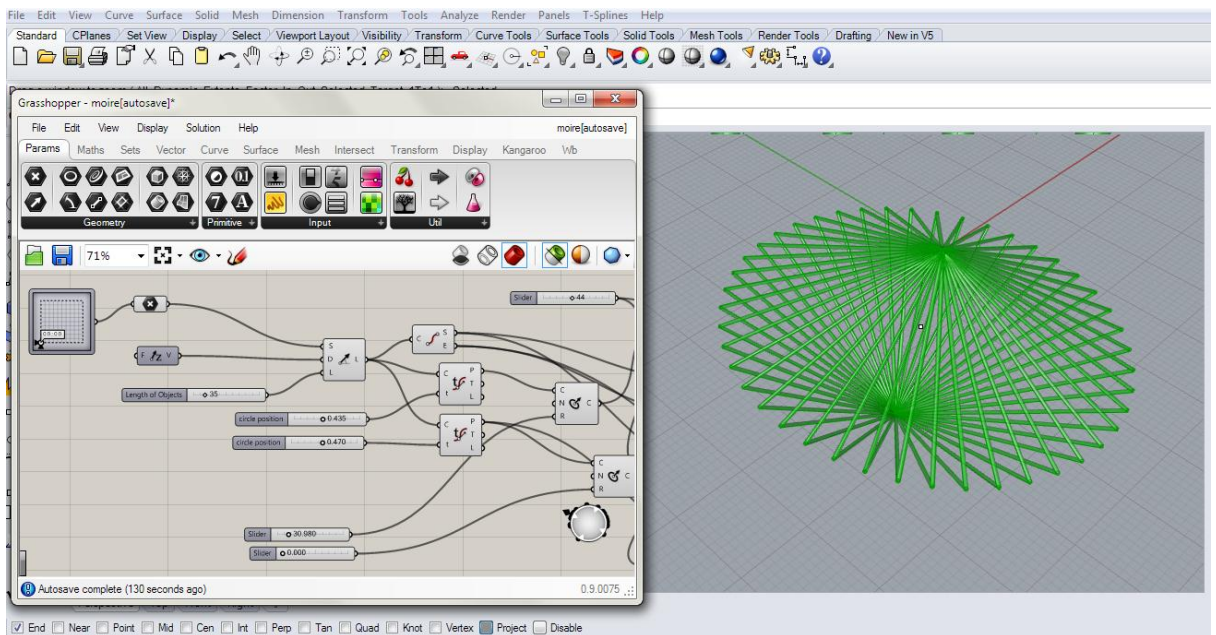
Figure 8-9: Screenshot of new, simplified Tool in Case Study

The designer returned to using a series of commands directly in Rhino to make forms suitable for nylon SLS printing. The main reason at the time for returning to a less automated process was that the computer would struggle with some of the more complex Boolean operations that were required to make the more solid and refined shapes the designer now required, often causing big time delays and crashing the software. Another factor was that computational tools can be time consuming to build, it was felt at this time it was more convenient to work directly and individually with Rhino tools in specified orders rather than trying to automate these steps.

The designer developed a new series of tools, in this case Rhino commands, to produce the desired shapes for printing. This series of tools or rules can again be viewed as a higher level tool, comprised of lower level tool in specific combinations. In shape grammar schemas the equivalent operation could be boundary schema transformations, but performed on a tool/rule, notated as $t(x) \rightarrow b(t(x))$. This activity can be modelled as taking a representation of tool or tool concept and reinterpreting it into a new tool, in this case a reinterpretation of a Grasshopper tool that produced simple design representations into a series of Rhino commands to create geometries suitable for 3D printing.

The new tool, comprised of a series of steps using existing Rhino commands is shown diagrammatically in Figure 8-10. This tool was used to produce pieces in the Phase jewellery collection, some of which are shown in Figure 8-11. Some variations used simple additions of shapes to create the fittings for the body to the cut cone shapes or segmentation of the original cone shape with Boolean subtraction operations.
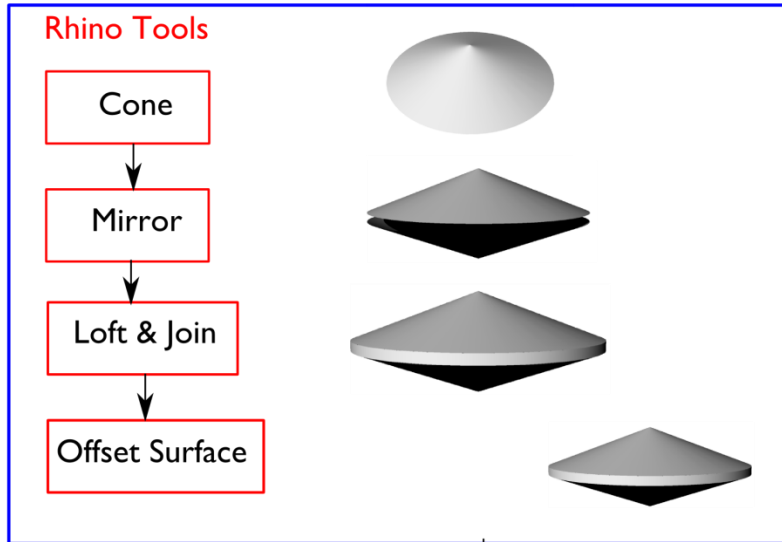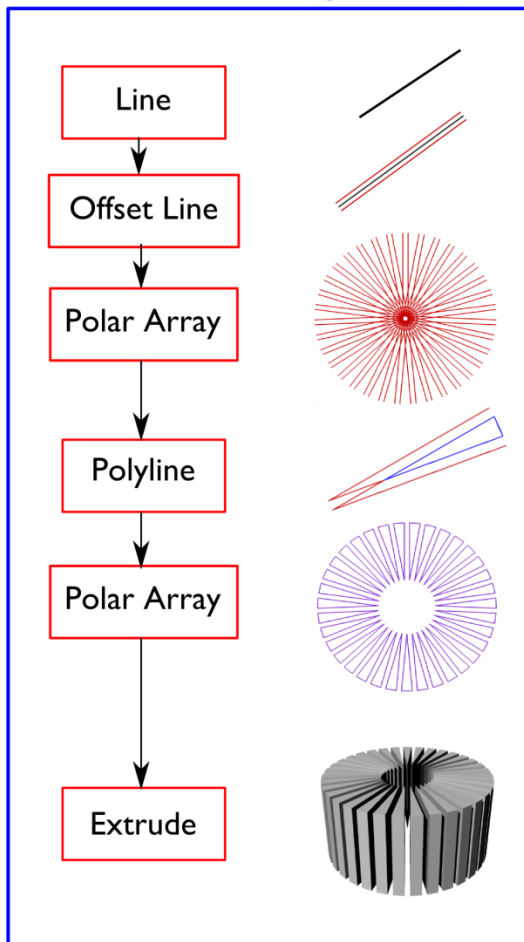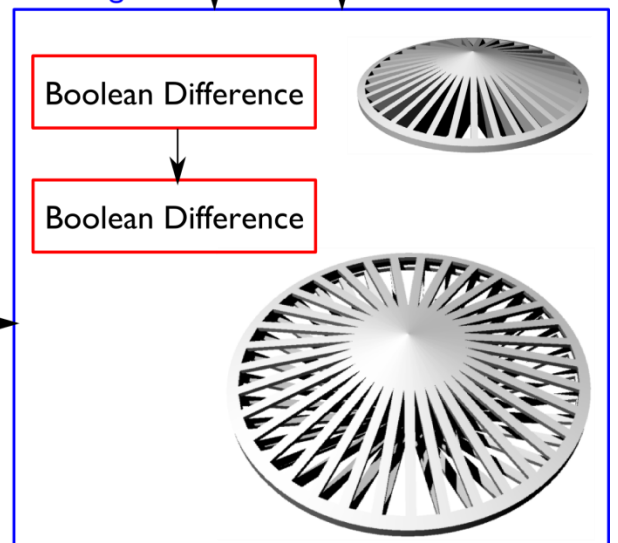
Figure 8-10: Template Tool for Phase Collection

Figure 8-11: Pieces from the Phase collection, Lynne Maclachlan, 2013

Some of these pieces were submitted again to the Goldsmiths' Craft and Design Council

Awards in 2013, they received a gold award for technological innovation, as shown in Figure

8-12, a section the relevant page in the 2013 awards catalogue. This award from a professional

body could be viewed as an endorsement of a successful making process and also a creative one, when taking into account that the award related to innovation.

Figure 8-12: Section of page from Goldsmiths' Craft and Design Council Awards catalogue 2013

8.5   Discussion of findings from Part I

From the interviews and case study creative episodes involving tools were found to concur with creativity literature, supporting the findings but also bringing new insights into designer-maker creative processes. Equivalent activities were found in shape grammar schemas, in the context of tools, indicating that the schemas are a valid way to formalise designer-maker creative activities and explain strategies for stimulating creative episodes. Revisiting a digital making process carried out by the author found further evidence that the new tool schemas could describe the key creative events of the process in a concise way. This section now rationalises the findings into a clear set of strategies that could be fostered by designer-makers and other to give an overview of how creative episodes can be encouraged in tool focussed design processes, this is a contribution to knowledge made by this thesis.

Three significant phases of activity were seen in the design-through-making processes investigated; these phases were often the site of the main creative episode in the design process:

- **Tool selection –** designers adding or subtracting tools as part of their design world.

- **Tool combination –** the way and order tools were used in making processes

- **Tool transformation –** the transformation of tools to produce new outcomes

These are now discussed along with the accompanying tool schemas that have been developed.

8.5.1 Tool selection

An initial selection of tools and materials was a key part in the designer-makers' design processes. Similarly in shape grammar addition schemas are used to introduce shapes to the design process, in preparation for further transformations. This can be notated in the style of shape grammar schemas as $\rightarrow t(x)$. Designers can add physical and computation tools into their design world, and tool concepts, with a view to using these as they are or transforming them.

The inverse activity of removing tools from a design world, $t(x) \rightarrow$, is also a valid way of producing creative episodes and outcomes. It was seen that omitting aspects of making process could give rise to interesting new features in designs, particularly in the work of designer Ian McIntyre, who expressed a preference for trying to remove steps in accepted making processes to achieve new results.

These schemas can be presented to designer-makers as a strategy to stimulate creative episodes by informing them to give more consideration to the selection and removal of tools in their personal design worlds. It is possible that some designer-makers may be entrenched in the tools they use due to being part of a shared design world with typical toolsets, countering the status quo of these toolsets could be a way to find new niche positions that they may not have fully or consciously considered.

A related activity characterised by progressing from Stiny's design rule schemas is that of re-identifying tools, $t(x) \rightarrow t(y)$. Taking a tool and using it in a new context, the tool does not

change, but where it operates on does, potentially giving rise to a creative episode. This can be allowed through creative mechanisms such as analogy, by finding appoint of correspondence in the two contexts. This is one way to assemble unusual tool sets a designer-maker could consider.

8.5.2   Tool combinations

After adding tools the designer-makers began the activity of using the tools. How tools are applied and the sequence they were applied in can produce large variations in the outputs of the processes. In creative episodes pre-existing tools were combined in new and creative ways and sequences to produce new outcomes. This tool activity can be characterised by the tool schema:

$$t(x) \rightarrow t(x) + u(x)$$

This schema represents the juxtaposition of tools in a tool series or amalgamation that are comprised of sub sets of tools that could be joined or merge in some way. For the designer-maker this can be presented as the strategy of considering and exploring tool sequences and combinations, looking for combinations that produce useful outcomes or ad-hoc tools comprised of others.

Related operations found in the evidence can also be proposed to designer-makers as tactics for seeking creative episodes. Isolation parts of tools, using the tool schema, $t(x) \rightarrow prt(t(x))$, either from physical tools or computational tools to examine them in more detail and possibly combine them into new tools directly.

The boundary tool schema, $t(x) \rightarrow b(t(x))$ offers the designer-maker the approach of taking some kind of impression from a tool, a new representation, most likely by converting it to a more conceptual perspective, which can then be re interpreted into a new tool. This is a powerful cognitive reasoning method with tools that can result in a personalised physical or digital tool being built to produce unique designs.

8.5.3 Transformation of tools

It was seen that the designer-makers often transformed tools, and these transformations can be categorised in different ways. Presenting tool transformation as a creative strategy to designers may be useful, and the different kinds of categories are now discussed.

Parametric transformations

Parametric tool transformations are transformations that change extrinsic variables of a tool. This is akin with the parametric transformation rule schema in shape grammar, and with the context of tools could be notated as:

$$t(x) \rightarrow t(x)'$$

This process can be used to make a range of related outcomes, such as a collection of related designs that share a design structure or style.

As a tool activity this suggests the strategy for designer-makers to explore any possible extrinsic properties of a tool, often parameters that are easily transformed and exist as part of the tool design, such sliding scales or variables in a computational tool. It was seen in the evidence gathered from practice that pushing tool parameters can provide emergent phenomena that the designer can choose to pick out and use creatively, for instance the appearance of Moiré patterns in the computational making design process that was analysed.

Functional transformations

Functional transformations are one of the most dramatic transformations a designer-maker can make on tools and therefore, according to Boden [10] may be high level creative activity.

Functional transformations on tools we used by the designer-makers studied to aim for creative design outcomes. A schematic representation of this can take the form $t(x) \rightarrow u(x)$, where a tool is transformed so as to be identified as a new, distinct tool. Transformations can range from new, related versions of tools to ground breaking, highly creative and personalised tools.

This can be done by using many of the previous tool schemas, by taking tool parts, $(t(x) \rightarrow prt(t(x))$ and impressions $t(x) \rightarrow b(t(x))$ and manipulating these with operations such as re-combinations $prt(t(x)) \rightarrow prt(t(x)) + u(x)$ and subtrations $prt(t(x)) \rightarrow$ to give new tools that can generate new designs.

As a strategy the designer-maker can be offered the idea that trying to create personal tools is a very fertile ground for producing creative outcomes. This can be done through applying the all the tool schemas presented in this research in an experimental and recursive way to different tool parts and concepts. The key to guiding this process are the established creativity mechanisms finding analogies, emergent features and blending concepts in conjunction with designerly knowledge to find relevant ways to work towards creative outcomes.

Distinctly new tools such as the digital silversmithing hammer by Hinton and the thread wrapping machine of Alverez can produce very original objects, as the designer-maker has created a new design world to explore, or a '*new craft*' as Alverez [4] claims. The difficult part of this kind of functional transformation is often realising these combinations in a working, physical tool, a design process in itself, taking time and commitment, as Hinton described in the interview, however the creative rewards can be substantial.

8.6   Reflections on shape grammar

Shape grammar rules have much in common with making activities. Knight and Stiny [65] have suggested that rules and shapes can be matched to '*doing and things*'. This thesis works on the basis of a similar but perhaps more specific analogy, interpreting rules and shapes as tools and materials.

Shape grammar rules can model simple material manipulations such as adding and subtracting materials throughout processes like clay modelling or wood carving, and acknowledge the complex objects that can ensue from specific and repeated application of such actions mediated by tools. The emphasis in shape grammar theory on '*seeing*' shapes in embedded

arrangements fits with the importance of the visual in making, makers carefully look for visual signals in materials as they are worked and use connoisseurship to appraise the work of their own and others. Knight and Stiny [65] work through some examples such as knotting and watercolour painting and claim that such processes follow the '*improvisational, perception in action approach of shape grammars*'.

Indeed this thesis has found that shape grammar schemas do make suitable descriptors for tool use in design-through-making processes, however a different emphasis on how this happened, particularly in creative episodes was found. Most making processes are mediated by tools, and aligning tools with rules, and materials with shapes, is a useful lens to model creative making processes. Rather than an improvisational and freewheeling approach to direct transformations on material to produce an object the designer-makers concentrated their efforts on selecting, sequencing and transforming their tools/rules, which in turn co-evolve design outcomes.

Figure 8-13 and Figure 8-14 show the two different approaches, represented in the style of shape grammar rules. Figure 8-13 models a series of tool applications on an object, each impromptu rule or tool applied to the object directly, the results observed and the next impromptu rule or tool is applied, the designer trying to drive the shape towards a desired outcome, as is typical in a shape grammar design process or theoretical model.
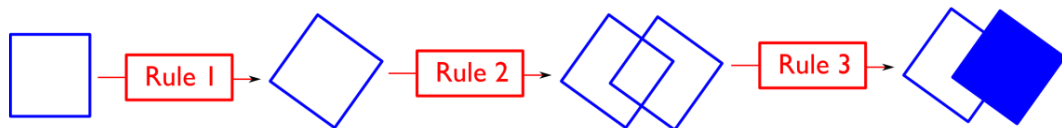
Figure 8-13: Model of shape grammar design process

The diagram in Figure 8-14 models the designer-maker process, a tool or rule is used, the outcome observed, then the designer return to the tool and makes the transformation here and then re-runs the tool in the hope of a suitable outcome.
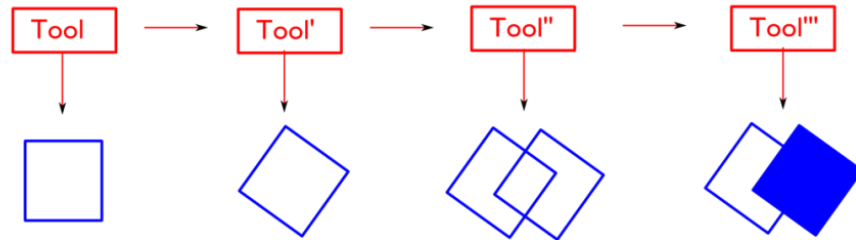
Figure 8-14: Model of designer-maker process

This difference between these two models is significant, and the second represents the findings of this thesis in professional designer-maker processes. Transformations that were important for creative episodes were sited on the tools rather than the objects. This is verified by Boden's [10] descriptions of creative activities, where rules are explored and transformed to make new conceptual spaces to generate new and valuable artefacts.

To reflect these findings back on to shape grammar theory, it would follow that rules can undergo transformations, not just shapes. Knight [55] and Chase et al. [3, 17, 18, 54] have shown that various kinds of rule modification in grammars can be used to produce new designs and design languages. This research has discovered that rules can potentially be subjected to all the transformations represented by Stiny's [109] shape grammar schemas, particularly if a rule can be represented or embodied as a material entity.

This was explored in the section on rule schemas, 7.1, where it was seen that applying the operations represented by the schemas to tools was possible and regularly performed by the designer-makers. The idea that shape grammar rules can be subjected to are a contribution of knowledge to shape grammar theory.

8.7   A framework for designer-makers

The first part of this thesis found that shape grammar schemas can clarify and communicate making processes involving tools, this enabled tool activities that stimulated creative episodes to be categorised. Designer-makers could use this knowledge to improve the chances of achieving creative episodes in a design process if presented these categories as a range of

strategies they could put into practice. A question exists about how best these findings could be presented for designer-makers in order for them to gain useful insights.

Stiny [109] represents the rule schemas in mathematical notation, and this has been extended to represent these schemas applied to tools, however it could be hypothesised that designer-makers may find this discouraging if they don't have experience of the field, although this can only be speculation unless tested. Introducing general ideas from shape grammar, such as viewing design-through-making as a process of transforming materials and tools with rules may have merit and would set the scene for a list of tool activities and descriptions with strategies and examples to guide the designer-maker.

Figure 8-15 shows an outline of the framework of the tool activities and strategies that could be used as a starting point for designer-makers wishing to stimulate creative episodes by considering tool activities in a design process in a digestible format. In addition it may be helpful if this table was accompanied with short descriptions of some of the real life examples found in this research, so the designer-maker could have a practical reference point to extrapolate from onto their own practice. Summarised versions of chapters 5 to 6 of this thesis could provide suitable examples of successful actions. These could be written and referenced in a table such as in

Figure 8-15.

The strategies could be presented in many different ways, from simple outline frameworks, to a book of varying length or even workshops involving chosen or given tools to introduce the ideas in a hands-on context. A longer length text or book could incorporate shape grammar style visual rules, similar to the one in Figure 7-5, which diagrammatically shows a hammer under transformation. How to communicate the strategies to designer-makers and how this impacts their practice could be an extensive piece of research, and as such is mentioned in the Future Work, section13.5, of this thesis.

Part I of this thesis looked closely at the role of tools in designer-maker creative episodes and has found that shape grammar, in particular shape grammar schemas are a useful way of clarifying the strategies designer-makers use and modelling their activities. Part II of this thesis(Chapters 9, 10, 11 and 12), and examines the use of shape grammar and shape grammar weights in computational making processes for generating objects for multi-material 3D printing.

Activity	Description	Strategies/Actions
Tool Selection	This phase is usually at the start of a design-through making process, considering what tools you may use and why could give opportunities for new making processes and designs.	Could you add new tools, from your field or from other fields of design or making? Could you substitute or even remove any tools from your making process to change what can be produced? * See chapter 5 for examples
Tool Combinations	Once tools have been selected consideration can be given to how they are used in a process. Trying out different tool combinations may lead to useful outcomes.	Can you change the number of times or order of tools used in your making sequence? Could you make an ad-hoc tool by assembling or combining a number of tools to produce something? * See chapter 5.4 for examples
Tool Transformations	Transforming tools can lead to new making processes and objects, these can range from small changes to entirely new tools which in turn may produce new and valuable objects.	Can you change any variables on your tools? (sliding scales, sizes, shapes) * See chapter 6.1 for examples Can you change or subvert the functionality of your tool in some way? (Hack or change the workings of a tool) * See chapter 6.2 for examples Could you build a completely new tool? * See chapter 6.3 for examples
Mechanisms to support creative tool activities	Certain cognitive mechanisms can be used to find appropriate opportunities for the above tool activities.	Analogies – can you find any similes and metaphors about your tools with other entities? Can you use these to produce new tool combinations or concepts * See chapter 6.4.1 for examples Concept blending – can you blend two tools or making processes to produce a new hybrid tool or process? * See chapter 6.4.2 for examples Emergence – look out for interesting features when using and playing with tools. Could these features be harnessed to seed new outcomes? * See chapter 6.4.3 for examples
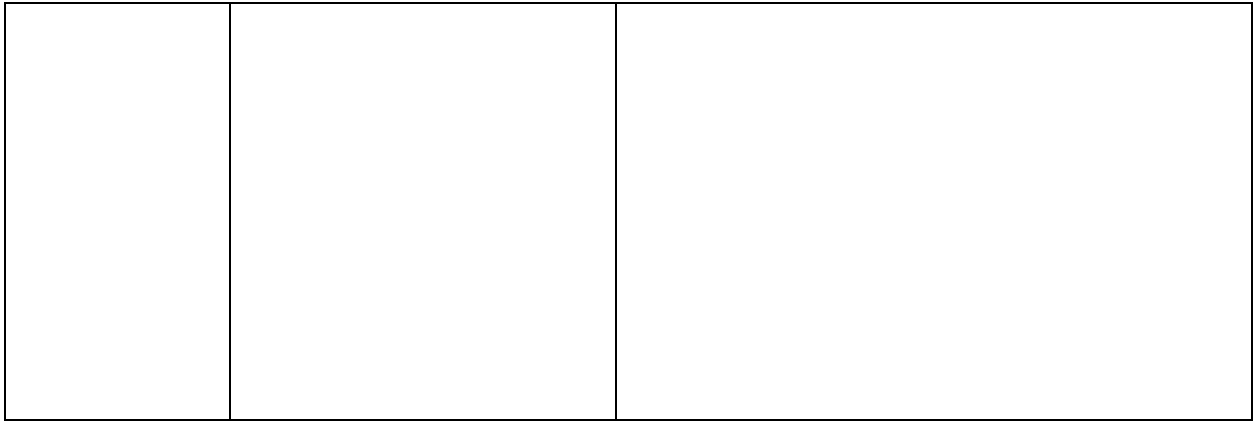
Figure 8-15:Framework for stimulating creative episodes using tools for designer-makers

In making processes material properties are also likely to play a part in some creative episodes as they have influence over how a tool transforms.

In shape grammar Stiny [106, 108] suggests that material properties can be represented by a weights system associated with shapes. Weights are attributed to shapes, when shapes in a transformation undergo Boolean interactions a system to resolve new weights for the new shapes is put in place. Weights have a numerical and computational basis, so may be suitable for managing and generating designs for multi-material 3D printing, a new range of technology that can print objects with variable properties.

Computational making is the use of digital tools, both software and fabrication to design and make objects, and is currently becoming the focus of academic researchers in the craft and shape grammar communities[15, 64, 65] and is being used and studied in real world design situations in different design fields such as architecture [81,37], engineering [98,99] and fashion [26].

In computational making digital representations of objects are transformed with algorithmic tools, and then realised with digital fabrication techniques, there is a disjoint in the form-giving. In physical making material properties are intrinsic to the material, affecting the results of transformations with tools. The disjoint in computational making between the digital representations and physical materials gives an opportunity to model or choose the way materials behave in the digital realm. A hypothesis was developed by the author that shape grammar weights, a system of representing material properties in shape computations, could be used to undertake this task.

To test this hypothesis a computational making process was performed as a method of *'research through design'* using small design experiments using weight systems to model various material property systems. The results are used to develop and refine shape grammar weights

tools for these properties and a more generalised weights schema as reference for designers undertaking a computational making process involving variable material properties.

The first 3D printing technology used in the experiments is multi-colour 3D printing, produced on a machine made by Z-Corp, it uses a powdered, gypsum based material which is bonded and then coated with ink to create objects with multi-coloured outer surfaces. This type of printing is readily accessible from many bureau services and in institutions and presented a useful opportunity to examine the use of colour weights in computational making.

The second type of 3D printing investigated is a machine called the Objet Connex, this machine takes cartridges of two or three resins which can then be mixed in different proportions in different parts of the object. The available materials vary in colour, transparency and flexibility and the availability to blend these results in a large spectrum of secondary materials.

These new technologies provide the potential for a greater range in the types of objects that can be fabricated than with single material printing. As Neri Oxman and Rosenberg [81] state, computational methods are typically restricted to defining and exploring the structure and geometry of a design models, and do not incorporate material properties or behaviour. The advent of these technologies show that material properties could and should be addressed in the computational process, and ways of doing this need to be developed. Neri Oxman [82] has championed the idea that materials and their properties drive design, taking the term material computational to identify the process of rules embedded in materials defining forms, with a basis in biological and craft processes. Oxman has demonstrated these ideas with the combination of digital computation and multi-material 3D printing, the resulting objects are representations of her overarching philosophy rather than a practical way of using properties to design.

This thesis aims to build on a similar notion of material computation, however with emphasis on applicable mechanisms – tools and rules - that designers can actually harness to bring about

material generation and transformations with current design and fabrication technology. This part of the thesis demonstrates a way to do this with shape grammar weights as one such mechanism for generating novel designs via computational tools.

9   SHAPE GRAMMAR WEIGHTS

As has been discussed previously, shape grammar operations as defined by Stiny [108], use shapes, composed of geometric elements: points, maximal lines, planes and solids, as a method to formalise and explore design representations. These computations adhere to the Boolean operations of sum, product and difference, and can be manipulated in affine and Euclidean transformations. However, shape computation can take into account non-spatial information, such as colour and function, and these are formalised in algebras of labelled shapes, V_{ij} and weighted shapes, W_{ij} by Stiny [106].

When applied to points, labels are markers used to control the orientation of rule applications where symmetrical or similar shapes are in use [108]. By labelling shapes different shape algebras can be made distinct, avoiding Boolean interactions, existing on separate layers much like the layer functionality in computer graphics packages [108].

Weights take labelling a step further and can represent properties of a shape, such as thickness on line elements, colours on planes elements or physical properties on solid elements. Unlike labels, overlapping weighted shapes may interact with one another; they can be embedded in one another and inherit weight values from the initial shapes or be given new weight values, the results of such interactions must be defined.

Stiny [108] proposed that weights systems adhere to Boolean operations and so definitions about how weights combine in shape sum and difference are made. He suggests the weight of the emergent intersection shape in a sum of two overlapping shapes is the maximum of the combined weights: so the addition operation for two of shape **s** with weights **u** and **v**:

$$(s,u) +(s,v) = (s,max\{u,v\})$$

such an operation can be seen in Figure 9-1, if shape **s,u** is placed on top of shape **s,v** and the weights are ordered as **u<v** then the resulting shape in this case is **s,v**.
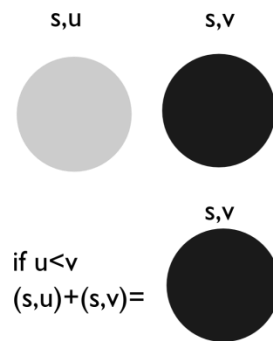
Figure 9-1: Weighted shape addition, s plus s

For two different shapes with an intersection, **s** and **t,** with weights **u** and **v,** the addition operation of **(s,u) + (t,v)** results in parts **(s-t,u), (t-s,v)** and **(s.t, max{u,v}),** three new shapes with associated weights, such an operation can be seen in Figure 9-2. Shape **s** is placed partially on top of shape **t**, a line highlights the edge of the circle to indicate the intersection shape **s.t**, but this border should not be visible at the end of the operation, **s,t** and **t-s** are embedded into one new shape with weight **v.**
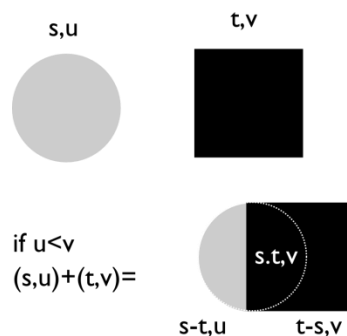
Figure 9-2 Weighted shape addition, s plus t

In the book Shape: Talking About Seeing and Doing [108] Stiny proposes that the weight difference between two overlapping shapes, **s**, is the product or the minimum of both, so for weights **u** and **v**, the subtraction operation is **(s,u)-(s,v) = (s,min{u,v})**. Figure 9-3 shows this

operation, if the weights are ordered so **u<v** the weighted shape resulting from the

subtraction takes on weight **u**.
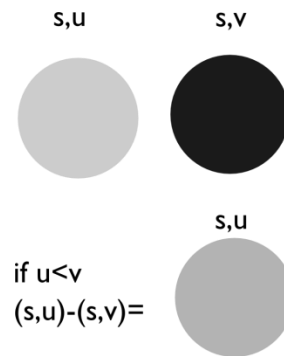
Figure 9-3: Weighted Shape Subtraction, s minus s

For two different shapes with an intersection **(t,v) - (s,u)** has parts **(t-s,v), and (s.t,**

min{u,v}), two new shapes with associated weights, this operation can be seen in Figure 9-4,

when **u<v** then **s.t** takes the weight **u**.
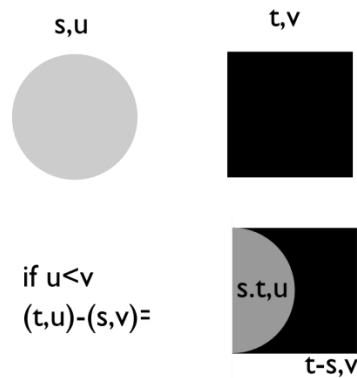
Figure 9-4: Weighted shape subtraction, t minus s

However in an earlier paper, where he first introduces the idea of shape grammar weights,

Stiny [106] also suggests that difference could be given a weight of 0, so for shapes **s** and **t**,

with weights **u** and **v**, **t-s** results in the parts **(t-s,v)** and **(s.t,0)**, as seen in Figure 9-5.

However whether this result leaves a blank space or a shape with a 'zero' weight is unclear.
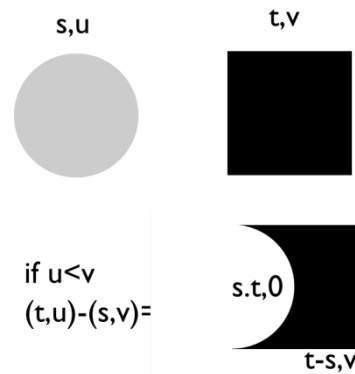
Figure 9-5 Weighted shape subtraction, zero weight result

Difference calculations may matter to the designer, not just for subtractive rules but for all further transformational rule applications. For instance a rule rotating a shape may look like a case of simply rotating the shape to the appropriate angle, however the underlying operation of a shape grammar rule is that of actually subtracting the shape(s) on the left hand side of the rule and adding the shapes on the right hand side of the rule, therefore theoretically two weight calculations of weight difference followed by weight addition should take place.

Knight [59] sets out an algebra for colour grammars, akin to Stiny's weights, by exploring possible rules that could be used to construct artists such as Mondrian's paintings. Lines and shapes become colour spots (equivalent to basic shape elements) and fields (equivalent to maximal shape elements) with '*qualitative*' differences that would not exist without the colour. When two colour fields overlap the spots that overlap 'fuse' to form a new distinct spot, in other word a new intersection shape with a colour. The colour of this new spot is dependent on whether the colours are, or are considered to be, transparent or opaque and the order they are placed on the page. Knight deals with this by a system of ranking colour fields to signal which field dominates others. If spots are ranked the same, they appear opaque and the final visual result depends on the order the fields/shapes are placed on top of one another on the page.

The operations for colour fields are again the Boolean operations used in shapes and weights. In a sum or intersection the rankings of the fields must be defined. As discussed the rankings

can allow one spot to dominate the other or they can be of equal ranking. If the spots are of equal ranking Knight suggests that the new coincident spot has a composite colour defined by the user.

For more clarity, Knight's colour grammar system [59] is exemplified below with and the accompanying Figure 9-6:

- The *sum* of two colour fields, F,g and F,y, contains the spots of the colour fields that are discrete from the second and vice versa, and the colour spots where these overlap. The colour of the intersection spot is defined by the designers chosen dominance ranking of F,g over F,y or F,y over F,g, or if the ranking is equal, the order F,y and F,g are placed on the page, or can be made a third colour, defined by the designer, in this case yg.

- The *intersection* contains only the coincident colour spots of the two fields, the nature of which are defined by the ranking system, order, or chosen colour, as above.

- The *difference* contains only the spots in the fields that are discrete from the subtracted field, leaving a colour spot with no colour, and so an empty space. This is where Knight's colour grammars are different from Stiny's weights, as Stiny permits a residual shape to be left with a weight calculated from the original shape weights.
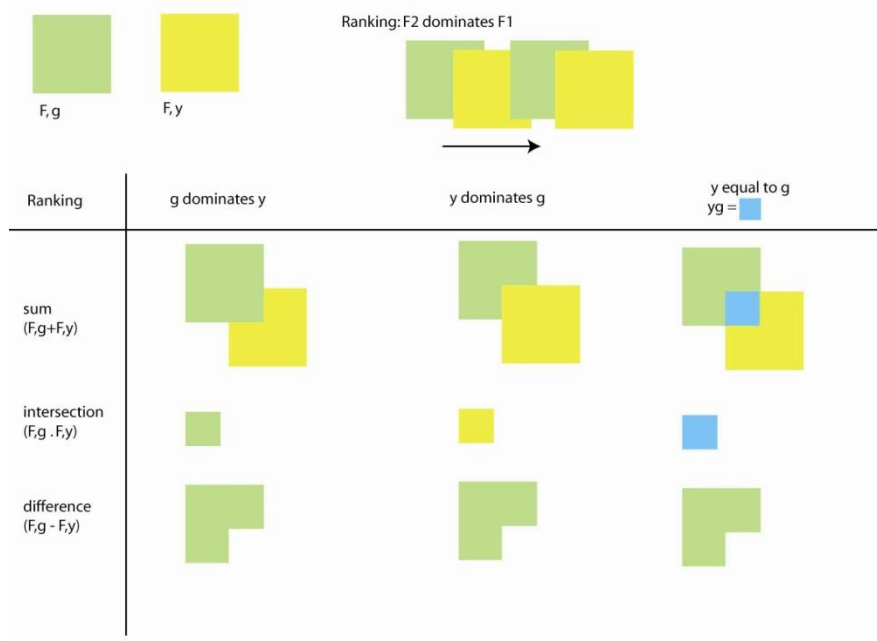
Figure 9-6: Knight's colour grammars

Knight builds on this colour grammar system in a later paper [61] supplementing the grammar of a form of traditional Persian garden where squares are recursively divided into further squares to create symmetrical garden designs segmented with borders and canals. Knight assigns colour to the new sections created by the recursive rules to signify different kinds of planting or canals in the designs.

This approach references a specified colour palette, in which each colour is given a ranking. If the one colour is ranked above another it will dominate and cover the other colour in any overlaps, as if it was opaque, so if $C_1 > C_2$, overlapped areas take on the colour C_1 . If the colours are ranked equally, $C_1 <> C_2$, at least one of the colours is assumed to be transparent and some kind of blended colour which appear in the overlapped area. Knight suggests a blending system whereby the palette consists of a range of colours with the same hue but increasing darkness, C_0, C_1, C_2…… and as a rule is applied the border colour of the rule blends with the colour already present and moves the colour up a step to the next darkest colour on the palette.

Knight suggests that any parameter can be used for ranking colours, with an associated method to calculate blended colours of the designer's choosing. Blended colours can be taken from a specified colour scale of colour, using modular arithmetic to round any calculation to a colour step on the scale. She also introduces the idea of parametric colour values, and suggests in this particular grammar colour could be varied according to the size and thickness of the borders in the garden designs.

The following two case studies look at examining and building on the weights and colour grammar systems presented by Stiny and Knight respectively and examining the application of these in a computational making design process using colour and multi-material 3D printing technologies.

9.1   Colour weights for colour 3D printing

Computational making is often undertaken as a process involving digital fabrication, technology such as 3D printing. 3D printing now has the capacity to produce objects with more than one colour and or material combined in one print. Many of these machines are now easily accessed through bureau services and academic and commercial settings, allowing designers to work closely with them. Therefore colour has become relevant in computational making situations.

One kind of machine which is readily accessed in made by the company Z-Corp, that can produce 3D printed objects with a colour coating; the process uses gypsum based powdered material sintered in layers using a laser, as the model is built the outer layer is coated in ink to produce a coloured model. This printer takes a set of ink cartridges, Cyan, Magenta, Yellow and Black (often abbreviated to CMYK), as many 2D printers do, and mixes these is appropriate proportions to produce a wide range of colours by applying proportions of tiny coloured dots in different densities to the surface.

The 3D printer requires a digital file to describe the form and colour of the desired object, for example Shapeways, a 3D printing bureau service, requests VRML (Virtual Reality Modelling

Language) files for this type of printing. In VRML files the geometries are represented by meshes of triangles and quads, the colour can either be assigned to each face or a texture map can be wrapped to the whole object which the printer software will then interpret to add the colour on the surface of the printed object in the appropriate areas.

Stiny's weight systems, previously summarised, are intended to offer a general weights system that can in theory be applied to a shape grammar to denote any material property the designer wishes to generate and transform. However within two published definitions he offers different options for weight differences [106,108] as detailed in section10.14. Knight's colour grammars [59][60][61] are specifically associated with colour and take in to account the attributes of colour, she also suggests that the designer and artist can use many different approaches for the manipulation of colour grammars beyond her versions. From this it is clear that no one definite system exists or is likely to be universally applicable.

The following section examines and extends the approaches that Knight and Stiny suggest in the systems they have formalised in more detail and in the context of colour, to ascertain the suitability of these for computational making using colour 3D printing. Simple experiments in two and three dimensions with coloured shapes demonstrate the application of the different weights rules and systems.

9.2   Colour in design

To give an overview of the relevance of colour in design processes and how the application of colour in computational design can be analysed, a short literature review follows.

Meerwin [80] provides an overview of the use of colour in design in the book *Color: Communication in Architectural Space*. He states that in the human designed environment colour serves as '*information, communication, and design material*', and lists some uses, which generally fall into two categories, that of informing and guiding the user of certain utilities or as a semantic signifier for culture, style or fashion. Human perception of colour is the interplay of

physiological and psychological effects [80]. Physiological effects of colour are influenced by the hue, nuance, placement, spatial function and any changes over time and psychological effects are rooted in experience, emotional effects, synesthetic effects and associated cultural symbolism.

Many artists and designers and scientists and philosophers have attempted to create colour systems and scales [40], where colours are arranged into schemes with some relationship with one another. Colour scales can be based on colour perception, the terms of which Wyszecki & Stiles list as: light, colour, hue, brightness, lightness, chromaticness, chroma and saturation [114]. And arrangements such as colour scales are a *'series of ordered numbers which represents observable gradations of a given attribute or gradations of attributes of color perception'* [P488, 114].

The Bauhaus painters, Itten, Klee and Albers examined the problem of finding a scale of equal perceptual steps between white and black [40] as did the painter Ozenfant [12]. Knight's [61] colour scale for designing Mughal Gardens, varies lightness, while keeping other attributes, such as hue, constant. Colour scales are usually represented diagrammatically as successive blocks of colour in a line or divided circle colour 'wheels' [100]. The intervals between successive colours can be defined by using an ordinal scaling, interval scaling or ratio scaling using a numerical value to represent the attribute [114].

Colour systems are ranges of discrete colours organised into geometric forms according to their relationships with one another. Countless systems exist, the website coloursystems.com [100] by academics Silvestrini and Fischer document over fifty colour systems from across science and art with details of the relationships and illustrations of the geometric forms these take. Da Vinci, Alberti, Goethe, to name some of the well-known, amongst others, all modelled systems [80]. Colour systems can take forms such as cylinders, double cone shapes, and even multi-dimensional lattices [114].

9.3   Ranking shapes

Weights systems require a way of ordering weights present in a design to allow the weight of shapes to be calculated in subsequent shape transformations. Ordering can be done in two fundamentally different ways, according to Knight and Stiny, either with reference to an attribute associated with the shape or an attribute associated with the weight that can be numerically represented. Knight suggests that the order of dominance for colour grammars when adding shapes to a design can come from the chronological order they are added to the design but later proposes that areas of colour can be ranked in any '*conceivable way*' [61] the designer chooses.

The following sections look at the possibilities for shape ranking systems in a computational making context, examining existing ways of ranking and extending these to new possible ranking systems.

9.3.1   Chronological ranking

Knight [59] suggests that a shape added to a design will always dominate those already present, following the model of placing opaque shapes on a page one after the other. In more analytical terms this would be a chronological ranking system, the colour of any intersecting area is:

$$C_1 + C_2 = \; C_2$$

where C_2 is the colour of the added shape.

Consecutive additive rule applications could result in a design like that seen in Figure 9-7, the sum of the colour weights is the weight of the last added shape. In Figure 9-7 the numbers on the shapes correspond to the chronological order they were added to the 'design' and so dominate shapes with lower numbers that their own.
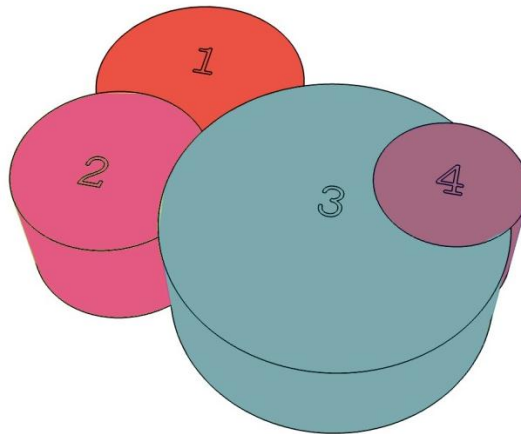
Figure 9-7: Colour weights dominating in order of addition to design

This means each shape in a design is given a numerical value as it is added to the design, which is then used to compare with other rankings to then inform the computational program on which colour any intersections inherits from the two coloured shapes.

To investigate the suitability of this approach in a computational making situation a Grasshopper tool was constructed which added consecutive cylinders to a design in Rhino 3D. Boolean operations were performed to find any intersections with existing cylinders and assigned the colour of the more recent cylinder.

The building of this computational tool required a number of recursive loops to be implemented, so the shapes were effectively ranked as they were generated and introduced to the design. This revealed that ranking shapes is a relatively simple task in a computational context as the inherent nature of coding requires the ordered lists to store entities.

9.3.2   Dynamic ranking

Chronological addition ranking may be fixed throughout shape grammar operations; each new shape added to a design is incrementally ranked higher than the last, however this need not be the case.

To take an approach from the first part of this thesis, if we view the chronological ranking of shapes in a design as a rule/tool we can seek to make transformations on this tool/rule in the hope of finding new and possibly creative episodes and outcomes.

Shape ranking for assigning weights in shape operations could be dynamic throughout the shape transformations, updated as rules are applied, either with specific rules or assuming that the shape identified for a transformation attains a new ranking in its selection. A system like this would be cumbersome in a sketched design process, but algorithmically simple to implement in a computational system, where assigning numbers and continually updating them is a straight forward task for a computer.

Dynamic chronological ranking also have the advantage of simplifying rules beyond simple addition rules. For example a shape subjected to a transformation shape rule, such as a Euclidean or affine transformation, could be re-ranked so that its colour would be given dominance in any intersections created by the transformation despite when it was previously added into the design.

Ranking rules could be embedded in a shape grammar rule. An example can be seen in Figure 9-8, a rule that moves a circle to the right also updates the weight ranking of the shape to one more than the maximum ranking already present in the design, when applied this allows the blue circle to dominate the black circle in the shape grammar design scenario below the rule.

This approach allows the current shape to dominate, mimicking the activity of lifting a piece of material a repositioning it in the design and avoids less intuitive results that may occur if the shape under transformation is ranked lower than shapes it interacts with as a result of the rule. Even a simple example demonstrating dynamic ranking reveals that it may be desirable and even necessary in some design situations include ranking information in a rule to ensure it operates in the desired way, much like Stiny's labelling systems [108], to avoid shape residues and unwanted embedding.
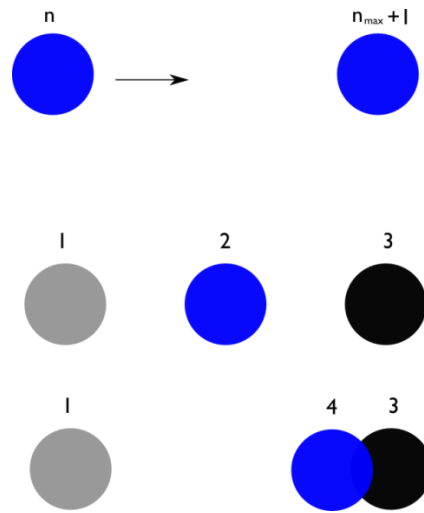
Figure 9-8: Dynamic Colour Ranking

The rule in Figure 9-8 which updates the circles ranking to make it the highest ranked object after it has been moved to ensure it dominates any other shapes it comes into contact with. It may also be useful to have rules which just change rankings, they could be applied to a shape to update its ranking before another rule is applied.

The advantage of dynamic ranking can vary according to how it is applied by the designer. Specific rules to control rankings in certain transformation rules could allow the designer tighter control of the behaviour of colours in the making process, which may be desirable. However allowing dynamic rankings to be parameterised with other shape attributes or even given randomised seeding could also offer a more unpredictable yet explorative process which may offer up new employable emergent features and interestingly complex objects.

9.3.3   Parametric attribute ranking

Ranking could also be parameterised according to shape attributes, any shape attribute that can be represented by a numerical value could be attached to a shape and used as a ranking for comparison, and these rankings could be static or dynamic. Examples could be properties such as size, geometric complexity, or indeed another attribute the designer wanted to make relevant in the design process.

An example of this is shown in Figure 9-9, the rank for resolving weights is taken from the number of sides of the shape. The result being that the weights of the shapes with more sides dominate the weights of the shapes with a lesser number of sides. When the triangle is translated up the page and intersects with the pentagon the green of the pentagon dominates the blue of the triangle. A similar system could be for many different properties, such as dimensions, areas, volumes of the 3D objects in a design for a Z-Corp colour print, ensuring that shapes with certain characteristics take precedence over others and preserving the geometry and properties of these, which may come in useful in certain design situations where continuity is required.
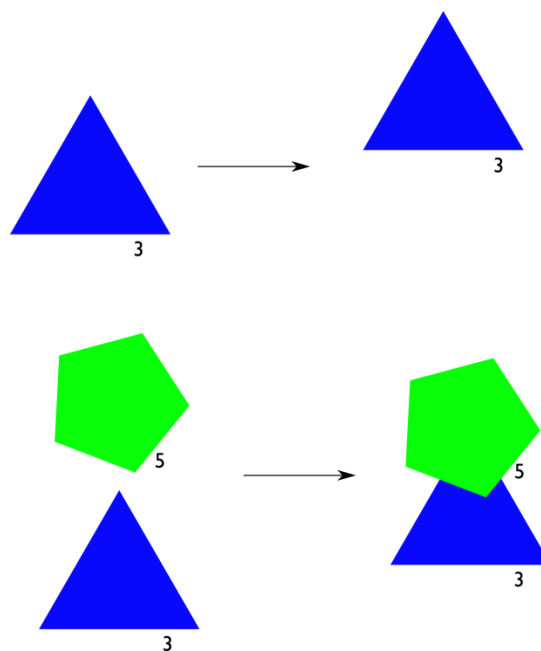
Figure 9-9   Ranking Shapes by number of sides

9.3.4   Ambient attribute ranking

Shape rankings could also be formulated from factors 'outside' the shape, ambient factors, such as the shape position or orientation according to coordinates or relative to other shapes, and again these could be static or dynamic though out the making process. Many of these factors would be easy to assign numerical values to and keep track of in digital design environment.
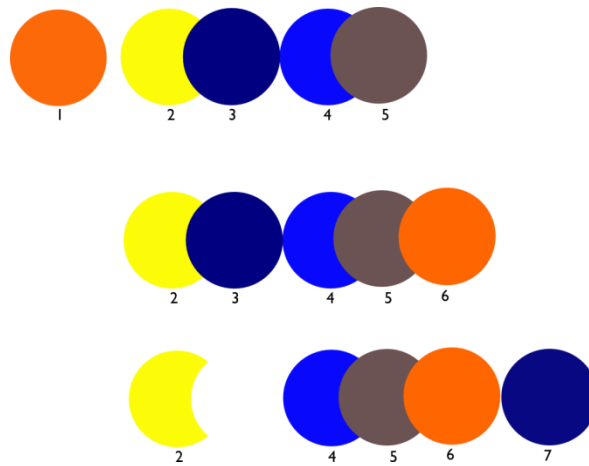
Figure 9-10 Rankings increasing with x position

A simple example of this can be seen in Figure 9-10, shapes are given rankings according to their current position in a design and as a circle is moved to the right by a translational shape rule the shape rankings are updated according to a function of their centre point position on an x axis. (Note on Figure 9-10: It may appear that there is some slight variations in the colours in the three steps, they remain the same, but may be affected by colour interactions making them appear slightly different to the eye as they are moved)

9.4   Equal rankings

Some shape ranking systems may return a shape with the same ranking with different weights, posing a problem of which colour should dominate the other. This could happen in the system from Figure 9-9, two triangles of different colours could intersect in the design, shapes with the same rank but different weights. Therefore such ranking systems may have to have a rule in place for situations where shapes end up with the same ranking but different colours. In one of her approaches Knight [61] suggests that shapes of equal ranking can be considered to be transparent, and so a blended colour of some kind is calculated for any overlap, effectively referring to a secondary system based on colour ranking.

The designer could handle equal ranking situations in a number of ways in their computational making process, other tactics could be employed if they wanted to avoid new colours being

introduced into the design, a random choice between the two colours or deferring to a secondary ranking system such as chronology.

9.5   Using shape rankings in difference calculations

Shape grammar also allows for subtractive shape operations, so the designer may need or wish to have a system for calculating weight differences. Also any transformational rule technically subtracts the shape(s) on the left hand side of the rule and then adds the right hand side. What may visually appear as a case of rotating or moving a shape is actually an operation of subtraction and addition, therefore a weight difference and sum calculation should take place.

Knight [59] and Stiny [106] both suggest that any subtractions of weighted shapes leave a zero weight, which they define as the complete removal of the shape. This approach has been assumed in the translational operation used in Figure 9-10, the blue circle is erased from the left of the design, leaving an empty space and visually a part missing from the yellow circle and added at the far right of the design. This example assumes that the blue and yellow circles have previously been resolved as their maxima according to the colour. Choosing the resulting weight of any shape subtractions to be zero is a suitable way to prevent shapes added to a design becoming inadvertently fractured in later transformations, such disintegration of initially chosen shapes may not be desirable.

However in a later definition of shape grammar weights Stiny states the weight difference between two overlapping shapes is the product or the minimum of both, so for weights **u** and **v**, **u.v = min{u,v}**. This system relies on the weights themselves having a numerical value, these systems are discussed in the next section. However a version of this could be developed in terms of shape rankings, a logical approach following from Stiny's subtraction calculation would be that the difference of two ranked, weighted shapes would be a shape with the colour and ranking of the lower ranked shape.
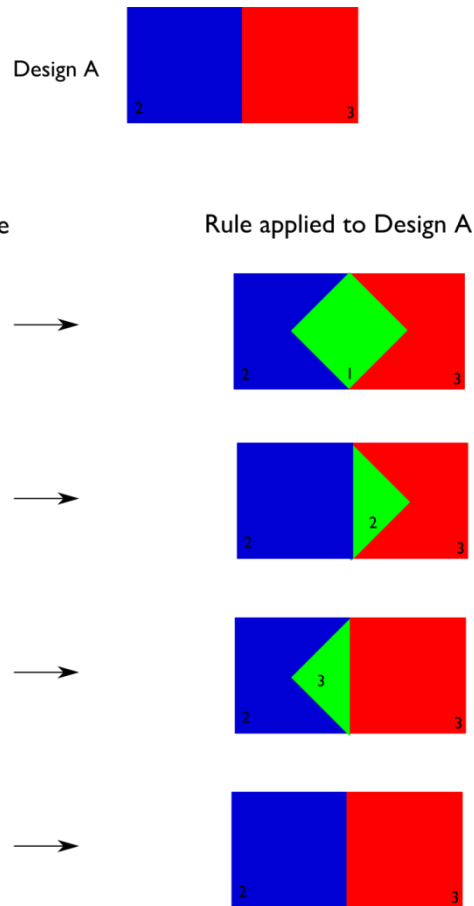
Figure 9-11: Shape subtractions using a shape ranking system

The ranking of an overlapping area could retain the ranking of the shape in the shape rule. For example the visual result of such an operation can be seen in Figure 9-11; a rule that subtracts a green square is applied to Design A, each example shows resulting design when the green square has a ranking between 1 and 4. When the green square is ranked lower than the shapes it is subtracted from the result appears visually as if the green square has actually be placed on top of the design, a counterintuitive result. If the green square is ranked the same as the shape it is being subtracted from the colour of the shape in the design is retained, visually having no impact. As previously mentioned in a situation where shapes that interact as ranked equally a secondary system for calculating weights can be used, either using a weight of zero or a blended colour weight. Finally if the green square is ranked higher than both shapes it is being subtracted from there is no impact on the design. Completely removing shapes from designs using this approach requires different rules. In this two dimensional example the background

can be seen as white, a rule that transforms the colour weight of the square to white would give the visual appearance of erasing the square from any other coloured shape. However this rule will not work for three dimensional shapes, as a white cube does not merge into a background.
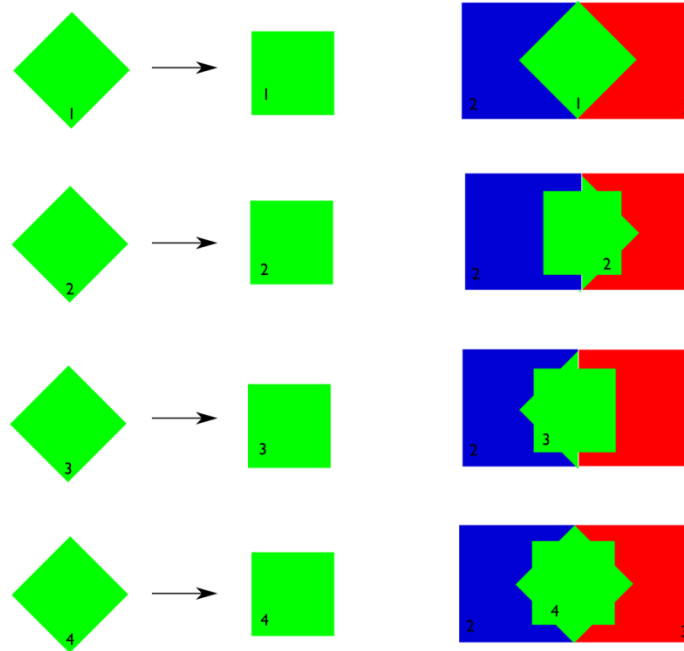
Figure 9-12: Shape Transformations using shape ranking System

Subtractions also occur in shape transformation rules, not just subtraction rules. Figure 9-12 shows an extension of the previous example where a green square is rotated, this is a calculation of subtracting the green square on the left hand side of the rule, as occurred in Figure 9-11 but the adding the new square, which has been rotated forty-five degrees, this rule is applied to the same Design A from Figure 9-11.

The first application with the green square ranked lower than the shapes in the design appears to simply add the square without rotating, this is because the addition on the rotated square has no effect as it has a lower ranking than the shapes in the design and is dominated by them. The next two cases where the green square is ranked equally with one of the shapes in the design, the subtraction is as in Figure 9-11 but then the addition of the rotated green square then dominates the colour of the shape with equal rank, using it chronological ranking to

resolve the colour weight. Other ways of handling this are equally valid, as mentioned previously equally ranked shapes could defer to another shape ranking system or a defer to a colour ranking or secondary colours.

In these examples the rule has allowed any new shape of the same colour to embed and inherit the rank of the green square in the rule. However the opportunity exists to transform rankings with rules at the designers will. Rankings could also be represented and used as variables, such a n_{max+1} or n_{min-1} to ensure a shape in a rule will dominate or not dominate other shapes already present in a design.

As can be deduced from this example shape ranking systems for calculating colour weights in intersecting shapes of different colours can produce counterintuitive result, if the designer is seeking creative opportunities exploring the unexpected shapes and forms generated by this kind of computation may yield some serendipitous outputs, leading to new creative ideas. If the designer wants results that behave in a more straightforward manner they may wish to erase shapes or default to a weight of 0 (which must be defined) from the design in difference operations, giving an unmodified space to then add transformed shapes to.

9.6   Ranking weights

Shape ranking uses a numerical value associated with each shape to be used in colour weight calculations, to resolve which colour will visually dominate in shape intersections. The second fundamental approach to weight assignment and calculation is to order the weights, or in this case colours, rather than the shapes, to establish which weights will be inherited by new shapes created by shape transformations.

9.6.1   Logic rule ranking

Knight [59] proposes in her colour grammar system that the colour of any intersection can be defined some colours to dominate others, colours are handled by descriptive rules such as '*blue dominates yellow*', '*green dominates blue*' and so on with potentially no limit on the number

of these. A design example following this logic is shown in Figure 9-13, where by the cylinders with the higher placing dominate the others.

Computationally logic rules could be used to handle this, in pseudo code:

IF *Shape1_Colour = Yellow* AND *Shape2_Colour=Blue* THEN

Shape1+Shape2_Intersection_Colour= Green

Using logic rules like this in a computational making tool for multi-material 3D printing would require that every possibility for colour interaction is included in a statement like the above. With possibility of many colours and interactions this could become cumbersome to code into a tool, although would allow very specific relationships.

9.6.2 Using weight rankings in shape additions

Alternatively each colour would be assigned a numerical ranking that can be compared, and the higher of the two selected to denote which colour is applied to intersected area, so that $C_1 < C_2 < C_3 < C_4 \dots C_n$. This is a simple and flexible system to implement computationally but does not allow for more complex colour relationships such as '*purple dominates red*', '*red dominates blue*', '*blue dominates purple*', a set of interactions that defy numerical ordering.
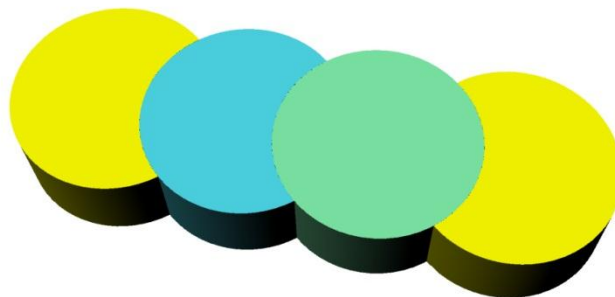
Figure 9-13: Example of Colour Weights by Ranking Colours

Assigning weights as numerical values is effectively the same as Stiny's definition [108] of weights. Numerical weight values are compared, and the overlapping area takes on the colour

ordered as the greater of the two. Like ranking shapes, this system can be modelled in a computational making tool; a list of numerical values representing the weight of each shape is used to calculate the weights of new shapes and updated accordingly.

9.6.3 Using weights rankings in shape differences

A method for shape differences may be required if the designer wishes to use shape grammar rules such as subtraction and also other transformations where a shape may be removed and a transformed shape added.

Using logic rules for subtractions as Knight suggested for additions is something that could be used. Common IF, AND, THEN statements, found in computer languages. Such as:

IF *Shape1_Colour = Yellow* AND *Shape2_Colour=Blue* THEN

Shape1-Shape2_Difference_Colour= Green

Giving results like the following example shown in Figure 9-14, a blue cylinder is erased from a yellow cylinder, the result leaves a blue residue shape if the blue colour is ordered as greater than the yellow. If the colours were ordered in the opposite way the rule application would have no effect on the yellow cylinder.
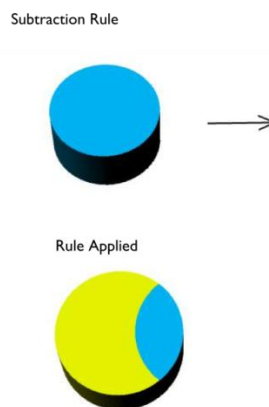
Figure 9-14: Shape Subtraction using logic colour ranking weights

Like using logic rules for resolving intersection in addition operations each colour would have to have specific rules to prescribe the result of each colour combination that may occur in the design. This offers the designer a high level of control to the designer of the outcome of colour weight calculations but also may become unwieldy in the programming of a digital tool.

Setting the result of any subtraction as a '0' weight, or a colourless shape, as per Stiny's system is also a possibility in a colour ranked system, with results similar to those in a shape ranked system, as can be seen in Figure 9-15, where a green square leaves an empty space, no matter how the weights are ordered, and appears white, the colour of the background.

Design A

Rule   Rule applied to Design A
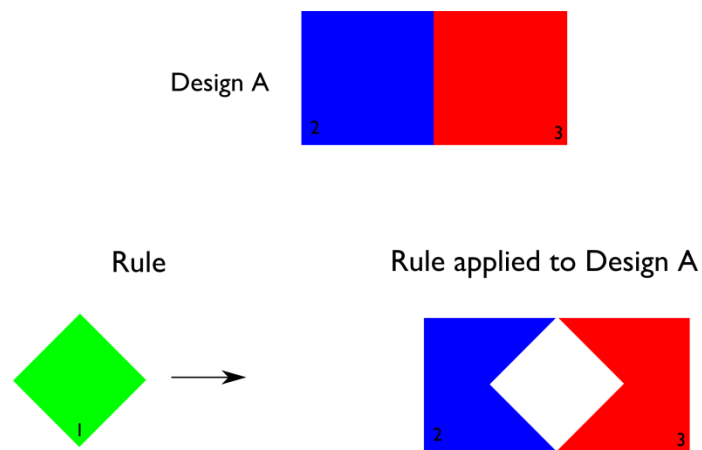
Figure 9-15: Colour ranking subtractions with 0 weight result

Following this system for other transformational rules, such as rotating a square, gives various visual results according to whether the colour of the square in the rule is ranked above or below the colours in the design, as seen in Figure 9-16.
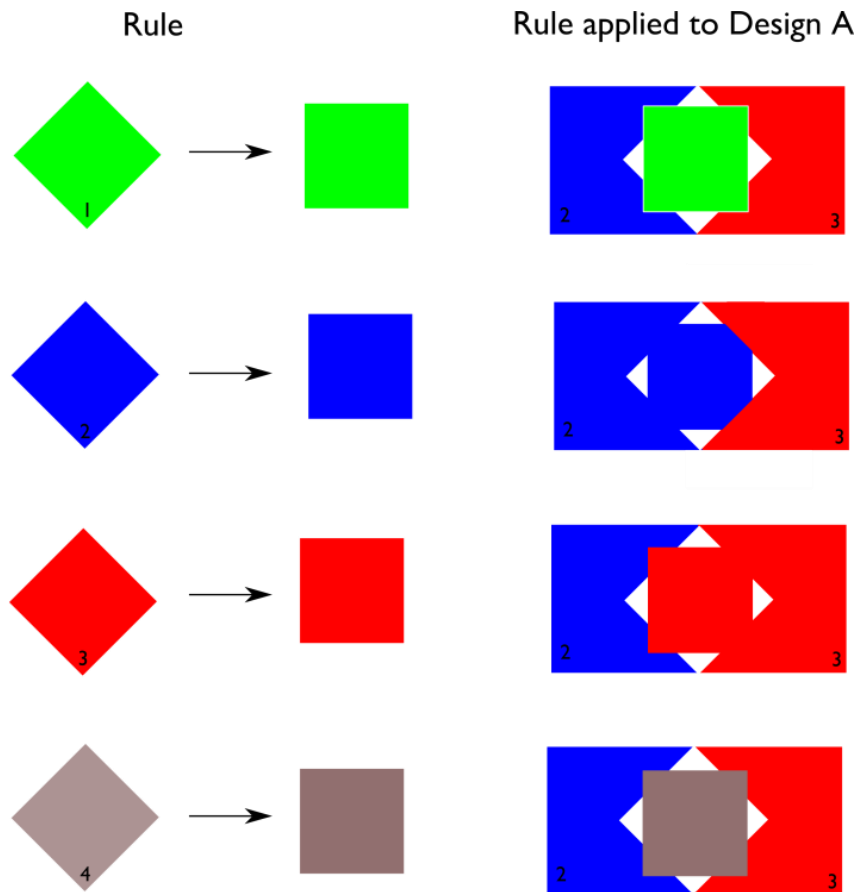
Figure 9-16: Rotation Rule applied using subtractions as 0

The visual results of such a system appear similar to coloured paper being cut and moved around, the square being cut out, changed colour and placed back into the design according to some layered position in the design.

The other choice again would be to have a system of ranking colours for subtractive operations, as in Stiny's definition where subtractive operations use the minimum weight value for differences, therefore a subtraction leaves the colour with the lowest weight value in any intersected area, as can be seen in Figure 9-17, which shows the results of shapes with different weight ranking being subtracted from Design A, the result dependant on comparing the weights rankings.
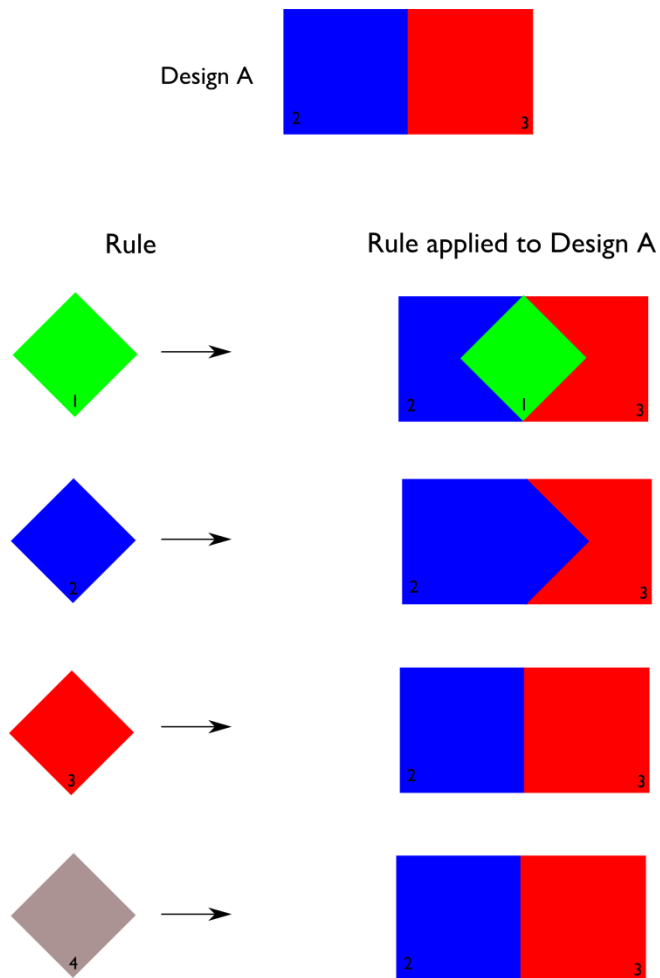
Figure 9-17: Deferring to lower ranked colour in subtractions

Like using shape ranking, minimum values for subtractions some of the results appear to have almost reverse effects of what might be logically expected, a subtraction of a lower ranked colour actually visually appears to add a square of this colour. Subtracting higher ranked colours have no effect on the design. Putting this system in place as part of a rotational rule, where the shape on the left hand side is subtracted and the new rotated square then added is shown in Figure 9-18.

Figure 9-18 demonstrates for colour weights, deferring to the minimum colour weight for subtractions will not tend to generate visually predictable results. Like using this system for shape ranking it may be down to the designer whether they want to use a system which is more visually predictable for generating designs for colour 3D printing or would prefer to

experiment with a less predictable system which may provide unexpected yet useful phenomena.

Rule   Rule applied to Design A
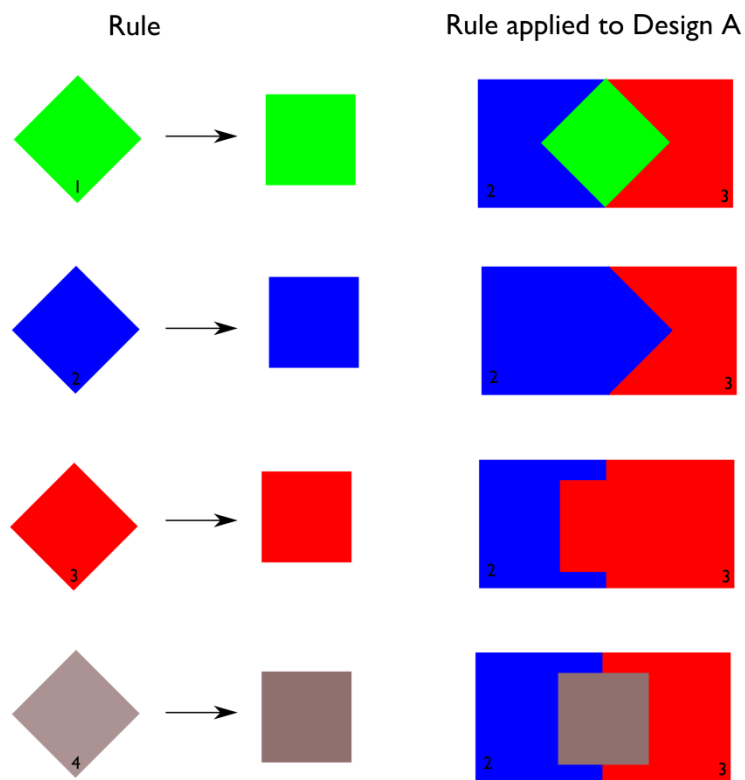
Figure 9-18: Rotation Rule Deferring to minimum Colour Weights for Subtraction

9.7   Calculating secondary colour weights

Stiny's system of weights only allows the weight of intersections after an operation be one of the weights of the original shapes in the transformation; transformations never introduce new weights, only colours in the rule or already present in the design can be used in intersections. Ranking shapes has the same characteristic, new shapes an only inherit weights associated with the original shapes before transformation. However a third approach is possible; to use calculations to produce new weights for the new intersection shapes that have some relationship to the original weights.

Knight extends her idea of rules to determine which colours dominate others to suggest that rules about the results of certain colour additions can be defined as tertiary colours, as if colours exhibit properties of transparency and adhere to rules such as:

Yellow + Blue = Green

Figure 9-19 shows a printed object where the author has selected a green colour for intersections between the yellow and blue cylinders. Again this could be implemented computationally with logic rules but would quickly become complicated to implement computationally as further rules would be required to handle every possible addition, the above may also require rules to define *Green + Yellow* and *Green + Blue* if more shapes are being added to the design and so on. The list of logic rules required would become exponential and therefore unmanageable fairly quickly in a computational system in comparison to an impromptu cognitive decision making process in a paper based design or art situation that Knight draws this idea from. This particular example uses a logic rule based on additive paint mixing, that a yellow hue mixed with a blue hue will give a green hue, but as Knight shows [59] it would not be necessary to follow the rules of physical colour mixing, the intersections could equally and easily be assigned any colour of the designers choosing using a computational rule.

Figure 9-19: Z-Corp colour print featuring designer defined weight on intersections

9.7.2 Modular scale colour weights

Knight [61], suggests another way of handling colour additions in the Mughal Garden designs. The recursive rule that successively subdivides the garden contains a colour, seemingly without ranking. Each time this rule is applied over a design which has a ranked colour and overlaps occur the intersection takes on the colour $\mathbf{C_{n+1}}$, where n is the ranking of the colour in the original design, and $C_0 < C_1 < C_2 < C_3 \ldots C_n$. In Knight's example each successive colour is darker than the last, but has the same hue. Knight doesn't specify the ranking of the colour in the rule, just the effect it has when applied.

Figure 9-20 shows a similar system applied to Design A, a square of some colour and size is added to the design, each time it is added the area intersected area becomes darker in colour, moving along the colour palette of a magenta hue, where the lightness is varied in successive steps of 20. Drawn up in Abobe Illustrator this makes use of the representative magenta hue from the CYMK colour system incorporated in the software package, the scale goes from 0% magenta to 100% magenta in 20% steps.
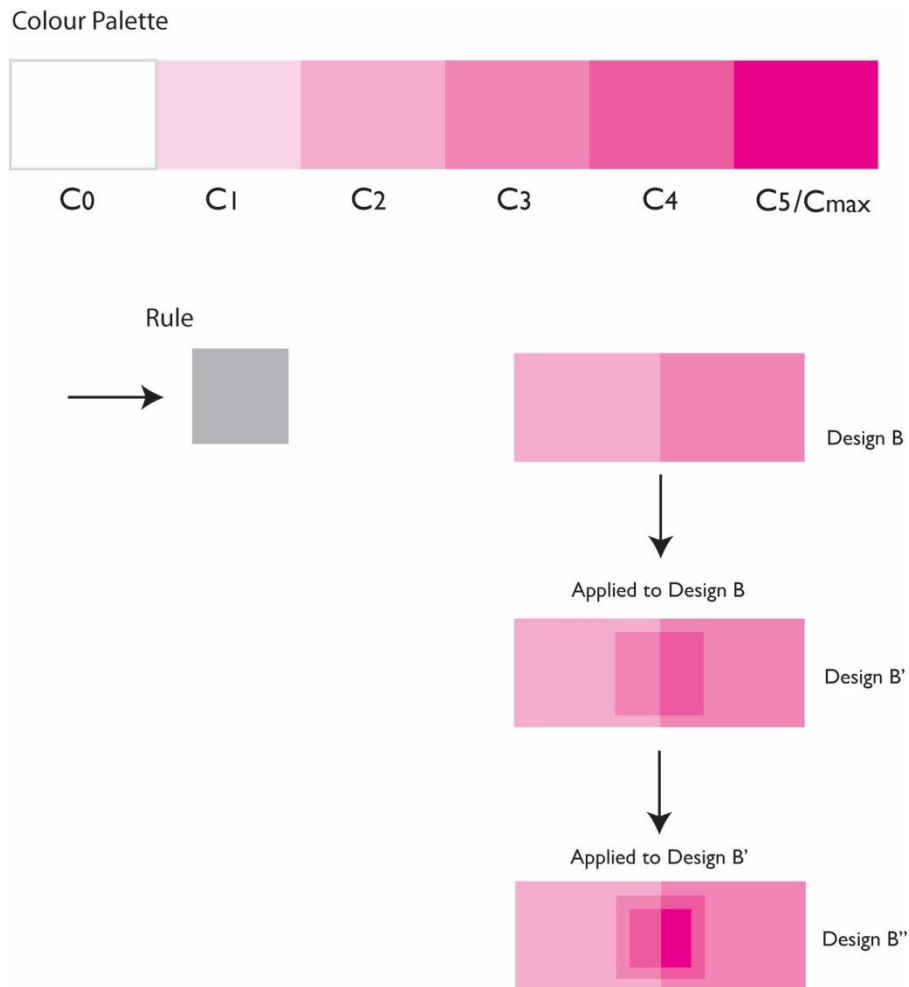
Figure 9-20: Additions handled as modular steps along a palette

As a square is added in a place of the designer's choosing the areas overlapped become one step more saturated with the magenta ink. This system introduces the possibility of a more schematic approach to colour transformations in shape rules, where the rule contains some universally applicable instructions about the colour change resulting from the rule use. Shape rules could also contain instructions such moving the opposite way on a scale, moving any number of steps along the palette, removing colours or leaving colours as they are. A more specific modelling of this is shown in Figure 9-21, where the rule contains some algebraic instruction for the colour of the added square, to move any overlapping areas along the palette one, two or minus one steps.
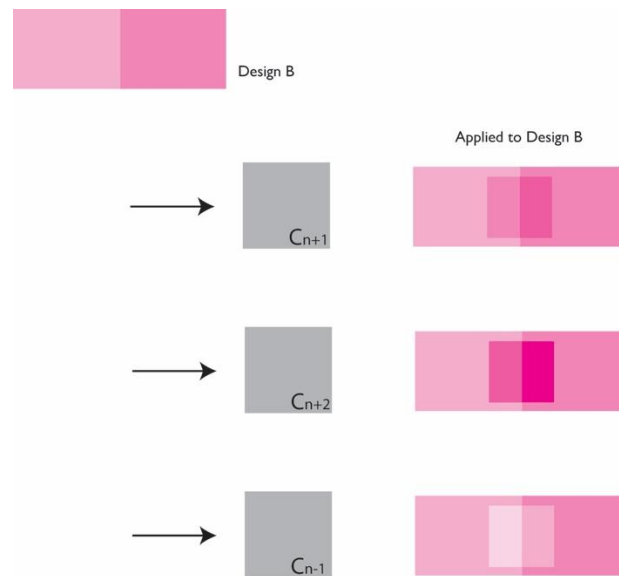
Figure 9-21: Instructive colour rules for one dimensional colour scale

Another system which can be extrapolated out of this system is that of directly using the numerical values of the colours, in this case the value of their magenta percentage. The values of the added square and square in the design are simply added to give a new magenta value. These values could be restricted to any number of steps between 0 and 100 by only using specific numbers in rules and designs, or by applying modular arithmetic to round up to specified colours as Knight [61] mentions.

Of further note is that one a shape in the design reaches the last colour on the palette, 100% magenta in this example, any further additions would not change the colour in the design, as can be seen in Figure 9-22, the second transformation of Design B would bring the value of part of the design to 120, but it is capped at 100. Equally if the colour has been subtracted down to the first colour, or 0% magenta, the blank space will not be changed by further subtractions, formally this means limits will be set for weight values if calculations are used and the designer should consider what may happen when these limits are reached.
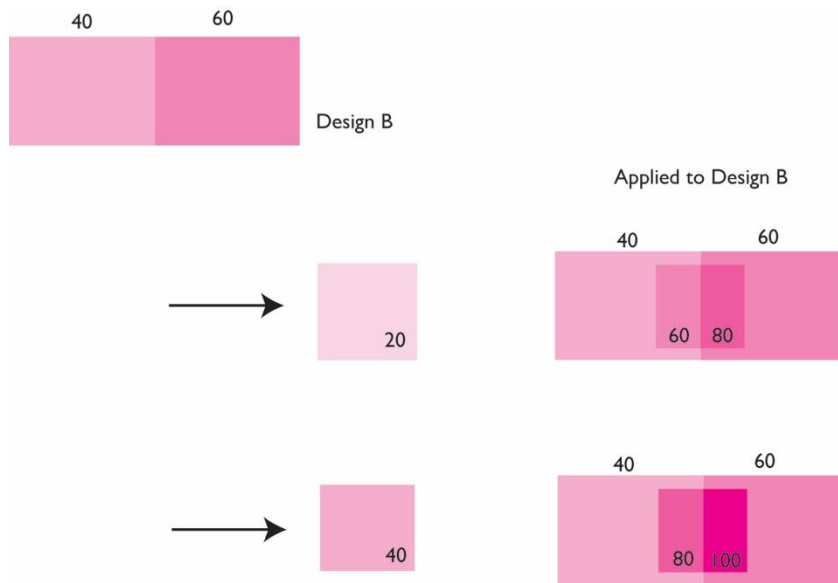
Figure 9-22: Consecutive rules reaching last step on colour scale

10 Z-CORP COLOUR PRINTING CASE STUDY

Section 9.1 has shown that there is a range of options for the designer to choose from when managing colour as weights in a shape grammar computational making design process. The designer must assign numerical identifiers to shapes or weights and then select a way of calculating from these the weights of new shapes produced by transformations. These examples have been based on an assumption that the colours used are from a selected colour palette comprised of a finite number of colours, ordered only by the designer, however computational design systems, and the underlying software and fabrication tools rely on specific colour systems to define the colours being produced on screen and on the printed object. Any colour in use by the designer is likely to be part of and defined by the colour system already integrated into the tools, these systems use numerical systems to define colours, so it makes sense that these numerical values could be used for weight calculations. This section examines colour systems available to use with Z-Corp multi-colour 3D printing and looks at ways they can be used in weight calculations.

10.1 Computational making with colour

Initial investigations into printing in colour with a Z-Corp gypsum based printer to establish how colour was managed by the software and the printer were carried out for the case study.

Rhino3D was selected as the most suitable software to carry out the computational making case study. While other CAD software programs for 3D modelling could be used, Rhino3D is used widely in the product and architecture industries, and is familiar to the author and can produce the VRML files required for this kind of printing technology so was deemed the best candidate for the task. Rhino3D also has the advantage of having the Grasshopper plugin, an algorithmic modelling program which can be used to create computational and generative programs to produce three dimensional geometry in Rhino3D, allowing a the building of flexible, personalised computational tools for design.

One way to assign colours to solid objects in Rhino3D to then be converted into a VRML files and printed is by placing objects in layers, each layer has a 'material' associated with it. Materials can be defined as solid colours, colour gradients or images and are mapped to surfaces or solids. Rhino uses the RGB colour space (Red, Green, Blue, the primary additive colours) to define colours of materials. The RGB colour space is used widely in digital, screen based design, to define colours and is based on the way red, green and blue light mix, Figure 10-1 shows a screenshot of the dialogue boxes used for colour selection and the layer menu on the right hand side.
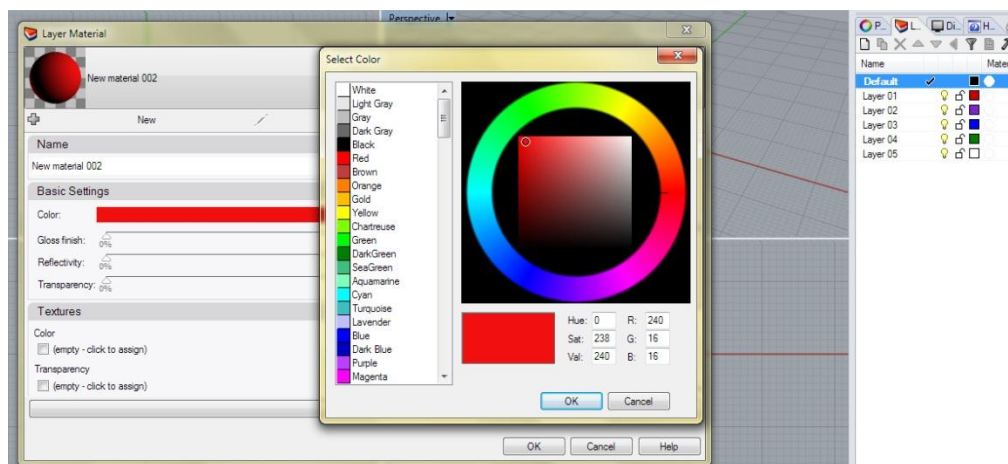
Figure 10-1: Screen Shot of Rhino3D, showing material options

Some initial experiments were carried out see how the printer would interpret the software use of colour. Some cylinders were assigned to different layers which in turn were assigned different solid colours, yellow and blue. The analogy of this is very close to that of labelling in shape grammar, shapes can occupy the same space and not actually interact with one another.

In the overlapping areas of the three dimensional shapes in drawn in Rhino, in this case primitive cylinders, the area that overlapped appeared onscreen as an fractured mixture of the colours of the two original shapes, this can be seen in Figure 10-2. This object was then saved as VRML file and sent to print on the Z-Corp full colour 3D printer.
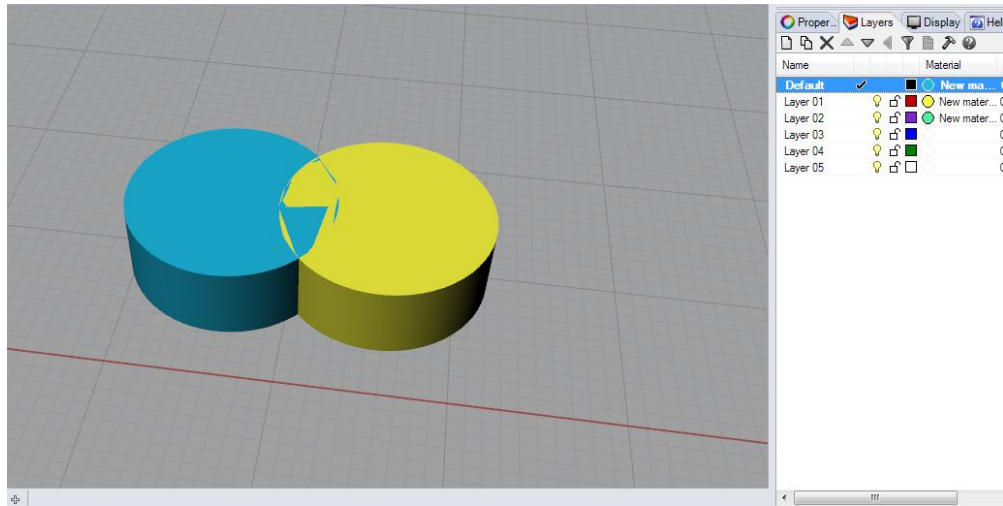
Figure 10-2: Colour Experiment in Rhino3D

The printed object exhibited a similar visual appearance on the overlapping area, with a marbled effect of the two colours, as seen in Figure 11-1. Viewed from a distance the area did start to appear green as the eye mixed the two colours.

Figure 10-3: Colour Print of Rhino3D model

This first experiment revealed that a computational colour system to handle colour assignment would be useful in a computational making system, as this particular software does not handle colour in overlapping shapes in a way that is likely suit the purposed of a designer. One possibility is to apply shape grammar weight systems to compute colours on digitally generated and printed objects as shape grammar weights can address the issue of assigning colours to overlapping areas.

10.2 Weights systems for 3D Z-Corp colour printing

After the initial experiments to see how Rhino3D would handle colour objects and how these would be interpreted into colour prints it was observed that a colour management would be beneficial. The following computational making design experiments test different shape grammar weight systems for ink coating colouring systems, of which Z-Corp colour printing is an example.

Rhino 3D and the VRML file system, and indeed most screen based software, uses the RGB colour system as a default as they are viewed on screens that use coloured light. However the particular 3D colour printing being investigated uses a different system, CYMK, which stands for cyan, yellow, magenta, and black, the four primary inks commonly used to create a range of colours on a printed page. Software, such as the Adobe software widely used by graphic designers, have in built algorithms to manage colour conversions, however CYMK colours on a printed page can appear to be significantly different from their RGB onscreen counterparts as the systems are physically different [8].

A designer using Z-Corp 3D colour printing has to make choices on how best to manage colour in their design process. They may wish to simply use the default situation of using RGB colour and accepting a standard conversion to CYMK. However if more control was desired the designer could create their own finite colour palette with RGB references on a physically printed CYMK object from the machine to ensure the final colours are as expected.

As has been demonstrated there is currently no definitive prescription or limitation on how shape grammar weights can be applied or used. The logical conclusion from the previous examinations is that weights definitions need to be modelled on the material properties in use and the outcome the designer is hoping to achieve.

To define a weights system for use in a computational making scenario the designer can begin by defining a relationship for the sum, product and difference for a given a given material property.

Generally, the operations of sum, product and difference can be defined similarly to the Boolean operations of union, intersection and complementation, as illustrated Figure 10-4. For weights *u* and *v*, the result of a sum operation, *u + v* subsumes both *u* and *v*; the result of a product operation *u · v* is what *u* and *v* have in common; and the result of a difference operation *u − v* is what remains of a shape after another is removed.
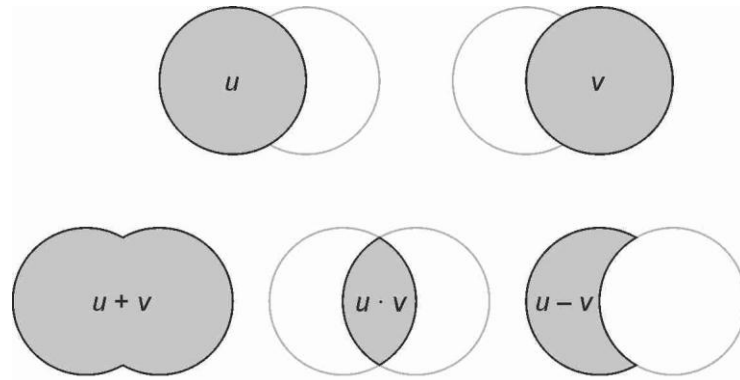
Figure 10-4: Weight operations as Boolean operations.

These concepts of sum, product and difference can be applied to available colour systems, providing a tool to assign colour in a computational making process. The following design experiments detail how this can be done.

10.3 Computational making experiments

To explore the possibilities of using colour weights to manage colour in computational making process a simple design brief was formulated that would allow the author to develop tools based on shape grammar weights with some context in real world applications.

The brief was to computationally design three dimensional interior textiles that could be printed with colour on a Z-Corp printer for use as screens or tiles in an architectural interior setting to enhance and segment spaces. Colour in an environment can have physiological and psychological effects on those present in a space [80], so it can be an important aspect of architectural design and making.

Computationally the initial designs use common rules from shape grammar; adding and subtracting coloured shapes within given area to create a three dimensional tile. The overlapping areas produced by these operations require a calculation to assign a colour to them.

This scenario provides a context to build computational tools that could help the designer-maker manage and explore shapes and colours for 3D prints. It was hoped that this design process would bring knowledge about the role shape grammar weights could play in this type of tool and symbiotically bring new theoretical knowledge about shape grammar weights.

A grasshopper tool was designed and made by the designer, the operation of the tool was a follows:

- Draw a plane

- Divide plane into grid points

- START LOOP

- Select a grid point

- Add a cube a point at a given angle

- Assign a random colour new cube

- Check for collisions with previously added shapes

- If collisions occur find the intersections and differences with previous cubes, add to list of shapes

- Calculate colours of intersected areas

- END LOOP

- Merge shapes and colours to produce tile

A simplified diagram outlining the operation of the tool, using CYM colours, can be seen in Figure 10-5.
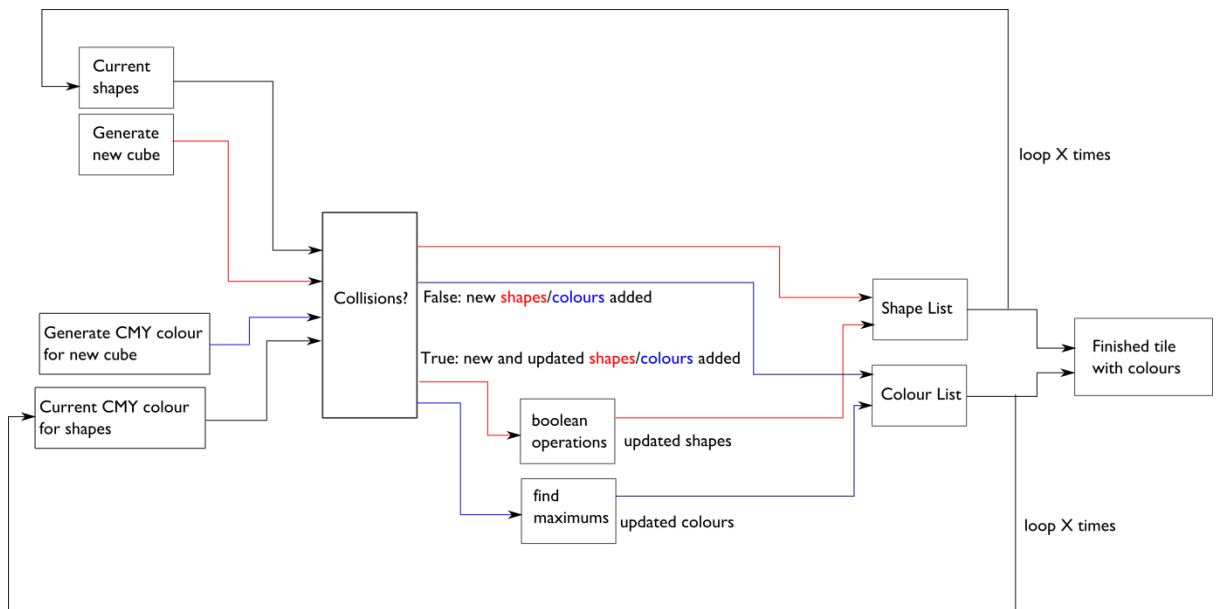
Figure 10-5: Diagram of Grasshopper Tile Tool

10.4 RGB and CYMK colour models

The first decision faced by the designer was to select a colour system to work with in the computational phase of the process. Z-Corp colour printing uses CMYK inks, as used in print systems to coat the surface of the gypsum based material. While software packages for two dimensional print designs often have CYMK colour tools inbuilt, Rhino3D did not. Rhino 3D operates on a RGB system, as CMYK printing was presumably not something envisaged by the creators of the three dimensional design software. The VRML files used by bureau services to communicate designs to the printer also use the RGB colour system.
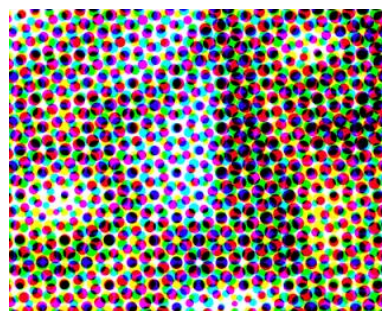
Figure 10-6 CYMK print magnification

In the CYMK colour system four channels are independent of one another, each value is a proportion of a full saturation of tiny dots of the given ink on a given area, a magnified view of

this can be seen in Figure 10-6, a large range of different colours can be visually produced as the tiny dots are blended by the eye. These tiny dots cover and gradually obscure the colour of the material they are applied to as the saturation of dots increases (usually white paper, or in this case white gypsum powder). Thus it is a subtractive process, as the numerical values increase the visual appearance of the colours becomes darker.

The RGB colour system is based on colour light mixing, the mixing of red, green and blue light hence the use of this system on electronic screens. In Rhino3D and other software the colour system it is represented by an 8-bit numerical system, where each colour is given a value between 0 and 255 for each channel. RGB is also usually accompanied in software by an alpha channel, a value of transparency for the colour. As numerical values get higher the colours appear lighter, as a saturation of light appears to the eye as bright white and no light appears to be black. Equal values of red green and blue create a grey colour proportional between white and black. When one channel has a higher value than the others the hue will shift in this direction relatively. This means the colour change from altering the RGB values is not always intuitive to the eye [9].

Software, such as the industry standard Adobe suite for media design, has algorithms for converting between colour systems. Conversions from RGB to CMYK can be problematic, often the CMYK colours appear duller and darker than their RGB counterparts and RGB has a greater number of possible colours, so exact matches are not always possible [97]. Grasshopper, has a CYMK conversion tool in which values between 0 and 1 are input for the parameters of cyan, yellow, magenta and black and an equivalent RGB value with numbers between 0 and 255 for Red, Blue and Green is the output. Any colours would undergo this conversion and then another back to CMYK before printing. It is likely the designer would have to allow some testing to ensure the final colours in a print were as they envisaged in the onscreen computational design process.

The designer decided to use CYMK values in the computational phase of the first design experiment. Using a system linked to the output of the 3D printer being used seemed appropriate, despite the conversion to the RGB system and back again, the effects of which would have to be evaluated upon receiving a finished print. CMYK also has the advantage that the channels are not coupled to one another in anyway, therefore the numerical and visual relationships of the colours could be more straightforward to use in calculations.

It was decided to keep the K value fixed at 0, in order that the colours would not become dulled by the black ink. The K value mainly exists in the CYMK system to allow the printing of black type, as the system is designed for use as a two dimensional paper based printing system, such as for newspapers and magazines. Even restricting system to three channels gives the opportunity to produce over one million colours if each channel could be a value between 0 and 100.

For a weights system the sum, product and difference must be defined for the designer to calculate the weight of any new shapes generated in shape transformations. The first iteration of a weights system for colour printing draws on Stiny's weight definition [106].

Stiny proposes that the sum of two weights, **w** and **u**:

$$w + u = max(w, u)$$

As CMY colour has three channels and therefore three numerical values associated finding the maximum between two CMY colours requires more instruction. Weights w and u are constructed as follows:

$$\mathbf{w} = (w_c, w_y, w_m) \text{ and } \mathbf{u} = (u_c, u_y, u_m)$$

As the values of CYM increase the resulting colour becomes more saturated with ink, so in this case it seems logical to equate higher numerical values as being closer to the maximum.

Following on from this the darkest or maximum colour of two CYM colours would be the one with the greatest sum of its three channels.

So if:

$$(w_c + w_y + w_m) < (u_c + u_y + u_m)$$

then   **w + u = u**

Alternatively if:

$$(w_c + w_y + w_m) > (u_c + u_y + u_m)$$

then   **w + u = w**

A visualisation of such a calculation can be seen in Figure 10-7, the sum of the CYM values of shape B's colour is greater than the sum of the CYM values of shape A's colour, therefore when the two are added the intersection inherits the colour of B.
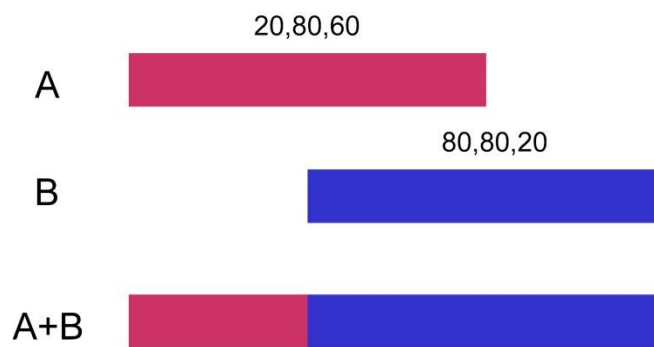
Figure 10-7: Example of an addition calculation for a CYM weight

A full tile design gives the opportunity to appraise the intuitive visual appearance of a weights system, Figure 10-8 shows a tile generated using the tool with this weight system. New shapes take on the colour of one of the original shapes, this gives the visual effect of some shapes overlapping others, shapes with more saturated colours dominate those with less saturated colours, as the calculation instructs. There is a possibility in this calculation that the sums of

the channels of each of the two colours may be equal, the designer may have to choose a way to select one of the colour in these circumstances, such a chronological ranking system to default to.
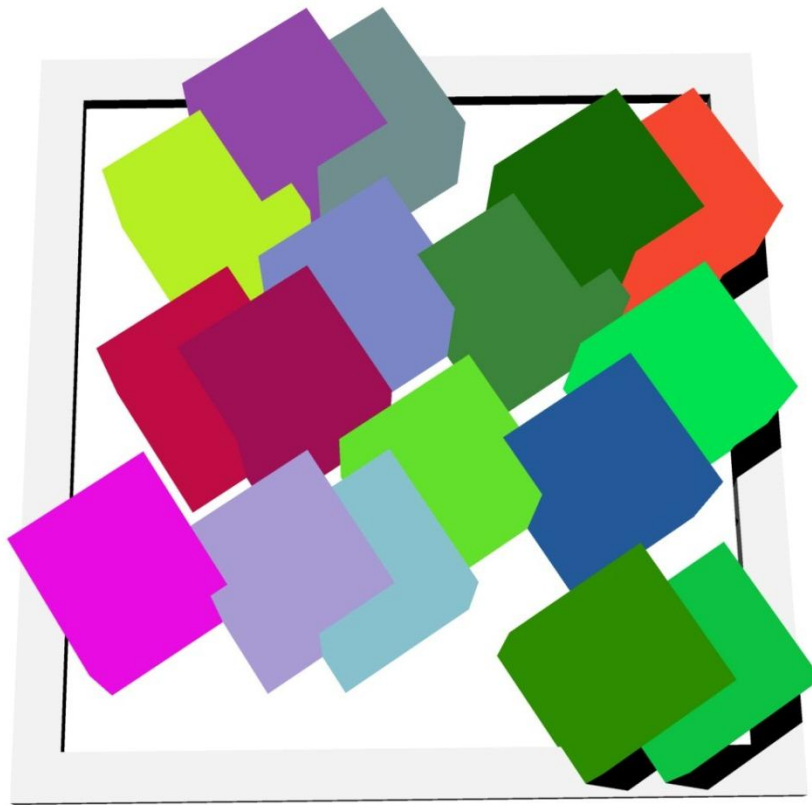
Figure 10-8: Tile showing addition calculations for a CYM Weight

Next a definition for the product of two CYM weights can be defined. Stiny does not define any systems for product calculations. A product contains parts of two parent entities, and provides a good option for when the designer wishes to give the effect of blending or transparency in a design for colour printing. In this case the channels can be compared independently to find the maximum of each and recombined to produce a third colour for the intersections between the shapes. So for weights **w** and **u**:

$$\mathbf{w} \cdot \mathbf{u} = (\max(w_c, u_c), \max(w_y, u_y), \max(w_m, u_m))$$

Figure 10-9 shows a visual example of this calculation of this product calculation, the product colour takes the greater of each CYM value for A and B, resulting in a new dark blue colour for the intersection of the two shapes.

Figure 10-9: Product calculation for weight using maxima of channels

A tile using this product calculation is shown in Figure 10-10. Visually it shows the outcome of this product calculation over a number of colour interactions. Using a product calculation would come into play if a range of shapes are placed at the same time or assigned different weights at the same time and the designer wishes to resolve the weight of shapes created by intersections. Performing calculations with the individual numerical values of each channel and then recombining produces secondary colours. In this case using the maximum of each channel does give the appearance that the secondary colours do have a relationship with the two original cube colours as if paint or ink was being mixed, with the secondary colour appearing to be more saturated than the two original colours.
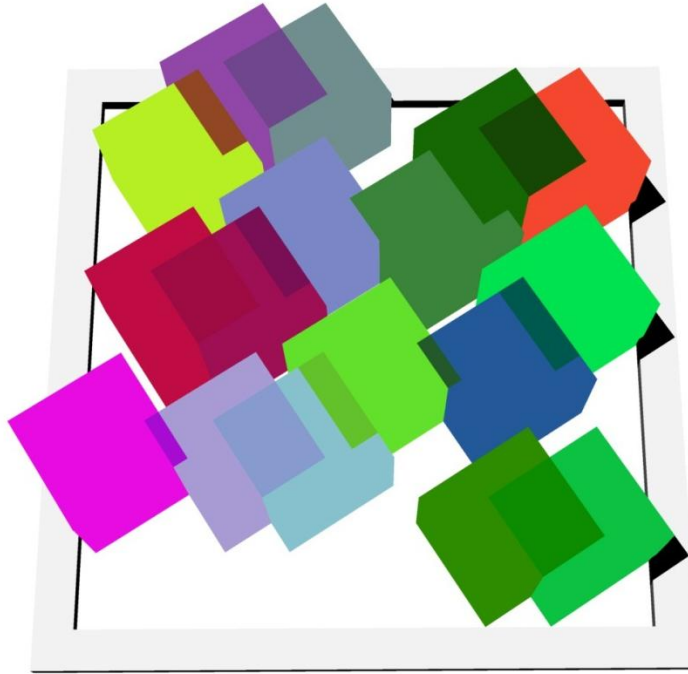
Figure 10-10: Tile design showing products using maxima for a CYM weight

Using the minimum value for each channel could also be a valid definition. So for weights **w** and **u**:

$$\mathbf{w} \cdot \mathbf{u} = \min(w_c, u_c), \min(w_y, u_y), \min(w_m, u_m)$$

And the visual appearance of a calculation using this definition can be seen in Figure 10-11, the lesser numerical value from the colour weights of shape A and B is taken an combined into a new weight for the intersection upon addition, in this case a magenta colour.

Figure 10-11: Product calculation for CYM weight using minima of channels

A tile generated tile showing a range of results using this product definition can be seen in Figure 10-12. Using the minimums of each channel to create a new colour also results in colour that have a visual relationship to the parent colours, however the colours are less saturated than the counterparts from the definition using the maxima.
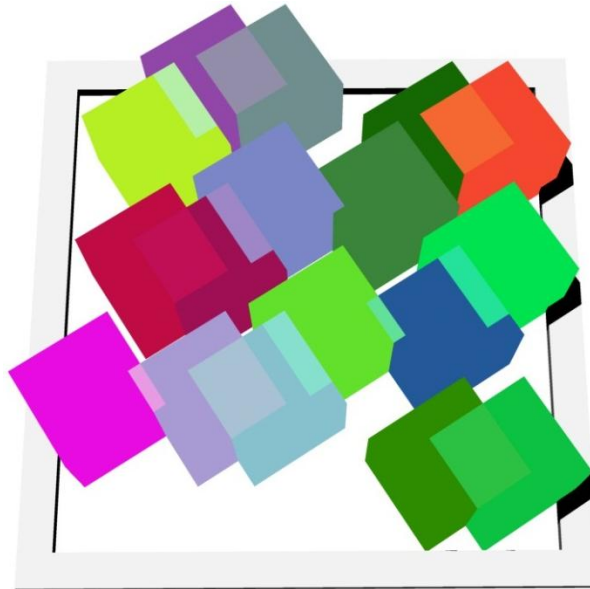
Figure 10-12 Tile design showing products using minimums for CYM Weight 1

These two different possibilities for the product calculation offer different aesthetic effects. The first, using the maxima of the channel creates a more saturated blend of the two parent colours, the other, using minima a visually lighter colour. The choice in which system to use is with the designer, a designer-maker can transform tools to produce the outcomes they see fit. To follow this example if the designer was making for an architectural space that they wanted to keep lighter and brighter deferring to the minima may be preferable. These approaches are only two of the possibilities, given two colours with multiple channels the designer can create a tool that defers, selects or keeps constant any of the channels in order to emphasise and tune the results to colour schemes they wish.

Finally a definition of a difference of two weights is required to complete the weight system. A difference is what is remaining once one weight is removed from another. In this case, following Stiny's definition, **w** and **u**:

$$w - u = min(w, u)$$

Like the addition calculation, three channels have to be taken into account, and again using the idea that a colour whose summed numerical channel values is less saturated and uses less ink than one with a greater summation we can take this colour to be the minima of the two. So if:

$$(w_c + w_y + w_m) < (u_c + u_y + u_m)$$

then $w - u = w$

Alternatively if:

$$(w_c + w_y + w_m) > (u_c + u_y + u_m)$$

then $w - u = u$

A visual example of such a difference can be seen in Figure 10-13, the sum of the channel values of the colour weight of shape A is less than that of shape B, so A is less saturated than B, and so the colour of A replaces the colour of B in any new intersection shapes created by the difference calculations.
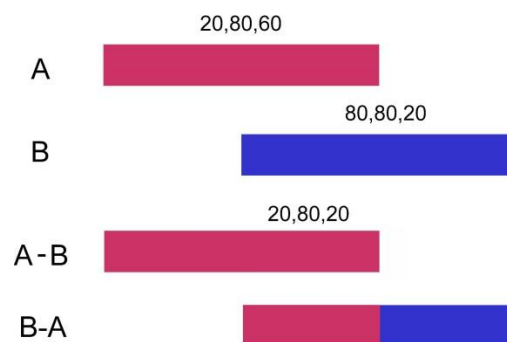
Figure 10-13: Weight subtraction for a CMY weight

Subtracting a greenish cylinder from the middle of the tile design in Figure 10-8 gives the new tile design in Figure 10-14. In this shape difference operation cubes that intersect with the cylinder that have colour weights with higher saturations than the cylinder weight change to

the cylinder weight, those with lower saturations remain unchanged. The visual effect is of a cylinder shape having been stripped out of some of the cubes.
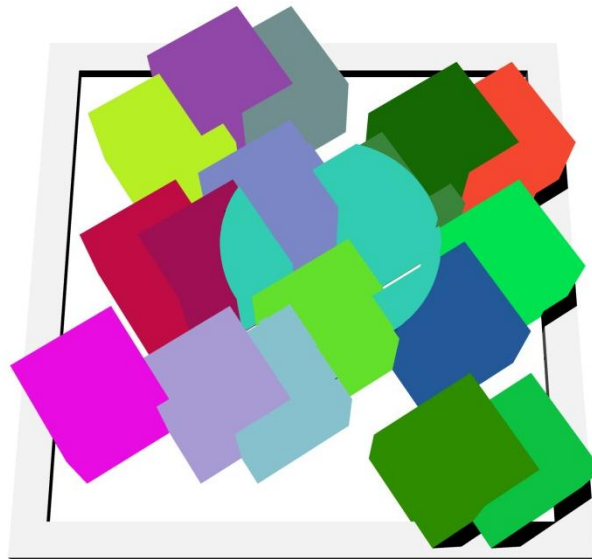
Figure 10-14 Tile design with green circle subrtacted

These three definitions of calculations for the addition, product and subtraction of weights for the CYM colour system adheres as closely as possible to Stiny's [108] general shape grammar weights definitions. Many more possibilities exist for ways to calculate the results of CYM weight interactions; three channels give the capacity for a large number of ways of comparing and combing colours to give colour outcomes for intersections, whether they are one of the original colours or a new colour for intersections. What this scheme does offer is a tool; a set of computational rules that can be used to manage and generate colours for overlapping shapes for designs for ink coated 3D printing. The tool could be used as is, but can also be transformed for new design scenarios, an activity was shown to be crucial for designer makers in creative design processes.

10.6 An RGB colour weight system

RGB colour values can also be used in Rhino3D and Grasshopper to define the colour of shapes. This section looks at how the RGB colour space could be managed with a shape

grammar weights system, by defining addition, product and subtraction weight calculations that complement the way the colour space is arranged.

The RGB channels each have a value between 0 and 255, however these channels are not independent from one another, an RGB colour is defined by the proportion of each channel to the others. For example a colour with the values 128,128,128 is a grey colour in the middle of black and white, changing the R value to 200 shifts the colour to a grey-red, up to 255 gives a dusky pink, as in Figure 10-15. Changing both R and G to 255 gives a slightly pastel yellow. These descriptions are from the onscreen colours as they appear. If you are reading this on a printed page the colour you are looking at are actually CMYK printed colours, converted by a colour management system.

| 128, 128, 128 | 200 128, 128 | 255 128, 128 | 255, 255, 128 |
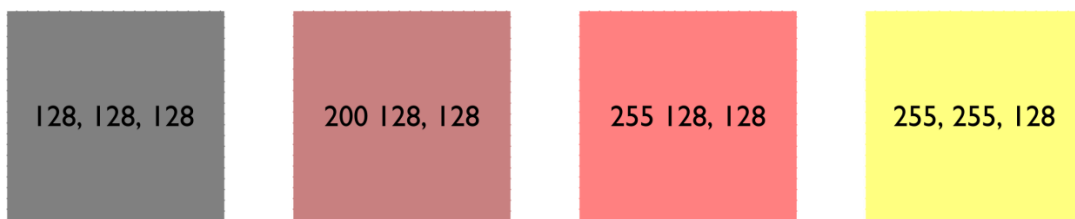
Figure 10-15 Examples of RGB values and colours

Therefore bigger numerical variations within the three values give more vibrant hues, as the values tend towards one another the colour tends towards a grey. As values increase the colours get lighter. The RGB colour system can be represented as a cube, using Cartesian coordinates in Euclidean space [9], as shown in Figure 10-16, shown using one hundred modular units.
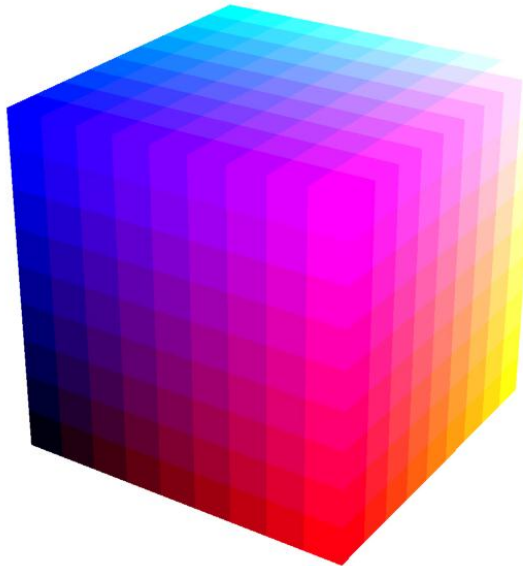
Figure 10-16 RGB colour space represented as a cube

Understanding the relationships between colours in a colour system aids the process of defining a weights system that makes sense for the designer. It follows that RGB colour requires different weight definitions from CYM as the relationships between the colours are different.

Again the sum, product and difference should be defined for the weights system. Starting with the sum and drawing again Stiny's general definition of sum for **w** and **u**:

$$\mathbf{w} + \mathbf{u} = \max(\mathbf{w}, \mathbf{u})$$

An RGB colour weight is composed of three channels, so:

$$\mathbf{w} = (w_r, w_g, w_b) \text{ and } \mathbf{u} = (u_r, u_g, u_b)$$

The maximum of two RGB colour could be interpreted as which one is lighter. Lighter colours have higher numerical values, as the amount of coloured light from each channel is increased and combined, lighter colours subsume darker colours. As the RGB colour space can be represented as a cube with Cartesian coordinates, a numerical value for determining how light or dark a colour is could be ascertained by calculating the distance from the origin, or black

(0,0,0) point corner of the colour space. Colours with larger vector magnitudes are therefore lighter and can be taken as the maxima, as they contain the greatest amount of coloured light.

So if

$$\sqrt{r_w{}^2 + g_w{}^2 + b_w{}^2} > \sqrt{r_u{}^2 + g_u{}^2 + b_u{}^2}$$

then: **w + u = w**

Alternatively if:

$$\sqrt{r_w{}^2 + g_w{}^2 + b_w{}^2} < \sqrt{r_u{}^2 + g_u{}^2 + b_u{}^2}$$

then: **w + u = u**

The visual results of such a calculation can be seen in Figure 10-17, the blue colour weight of shape B dominates in the outcome of the weight of the intersection in the addition as this particular colour has a larger magnitude by around five units.
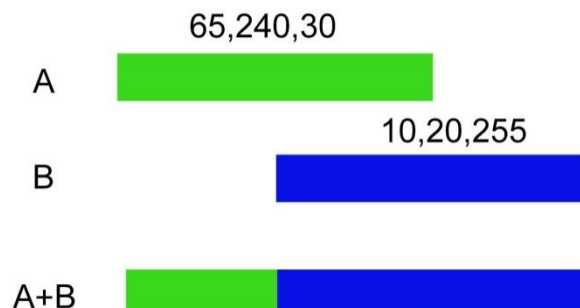
Figure 10-17: RGB weights addition calculation

Figure 10-18 demonstrates how the definition can be used to calculate the colour of intersections in a tile design, this time calculating the magnitude of the two colours involved in an intersection, comparing and assigning the colour with the greater magnitude to the intersection and giving the appearance of the cube with this colour weight overlapping the other.
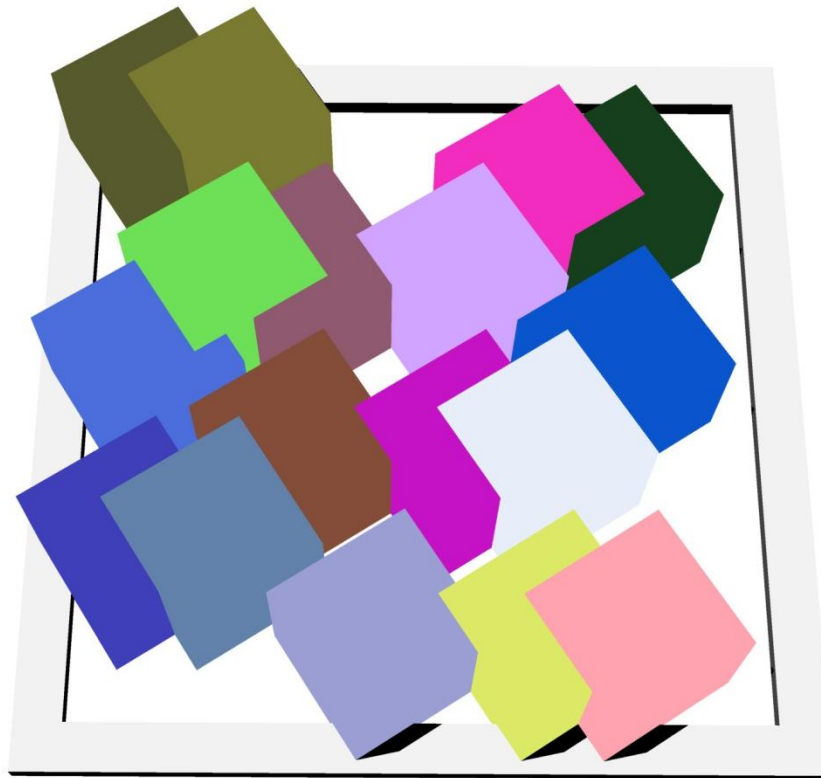
Figure 10-18 Tile designed with an RGB weights system showing additions

Some different colours will be the same distance from the origin point so the designer will have to choose whether to default to one of the colours by chronology or some other system.

If the designer wishes the opposite visual effect, modelling the weights system to consider darker colours as more dominant, they could simply change the calculation for colour weights to favour the minimum value colour and apply to intersections; again the designer can take this tool and transform it to suit the aims of their own design and making process.

To define the product for RGB weights we must consider how to calculate a colour which contains a part of both parent colours, this could be defined as a colour in the colour space at a point between the two. So the product of colour weight **w** and **u** is:

$$\mathbf{w} \cdot \mathbf{u} = \left(\frac{r_w + r_u}{2}, \frac{g_w + g_u}{2}, \frac{b_w + b_u}{2} \right)$$

Effectively the same as averaging each channel to create a new colour, a numerical example can be seen in Figure 10-19, each channel in the two colour weights of shapes A and B have been averaged, returning a new bluish green colour for the intersection.
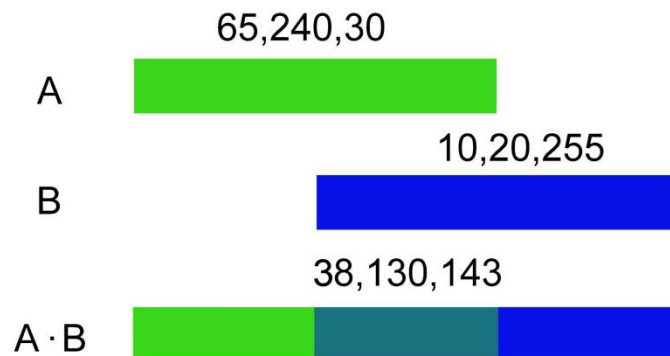
Figure 10-19: RGB weights product calculation

Figure 10-20 shows the same tile using this calculation, using the same randomly seeded input colours as the tile in Figure 10-17, it can be seen that averaging RGB channels will tend to drive the colours to less vibrant hues, as the closer the numbers of each channels, the closer to grey the RGB colour becomes, but does give the visual effect of the two cubes having a transparent quality that creates a mixed colour in the overlap.
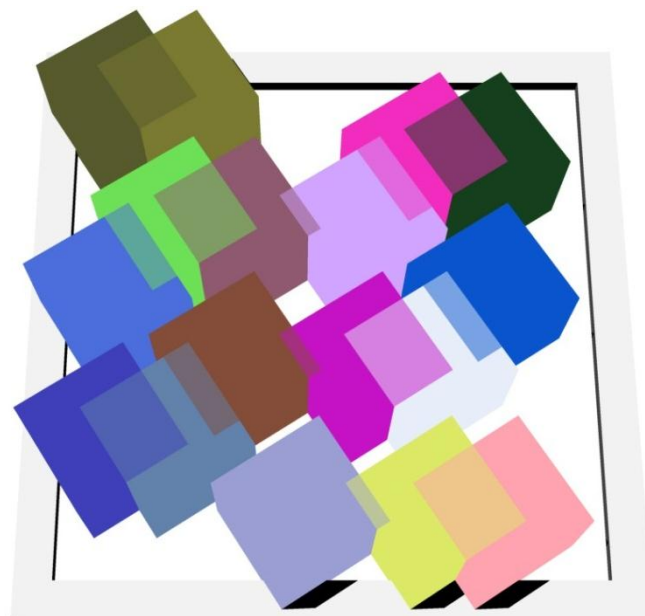
Figure 10-20: Tile design showing RGB product weights

Finally to define a difference calculation for the RGB weights system we can draw once again on Stiny's definition of taking the minimum of the two parent weights the difference of two RGB weights can be defined as:

$$w + u = \min(w, u)$$

An RGB colour weight is composed of three channels, so

$$w = (w_r, w_g, w_b) \text{ and } u = (u_r, u_g, u_b)$$

The minima of two RGB colours as the darker of the two, having lower numerical values as they contain less coloured light. Colours with smaller vector magnitudes are therefore darker and can be taken as the minima, as they contain the least amount of coloured light. So if

$$\sqrt{r_w{}^2 + g_w{}^2 + b_w{}^2} < \sqrt{r_u{}^2 + g_u{}^2 + b_u{}^2}$$

then: $$w - u = w$$

Alternatively if:

$$\sqrt{r_w{}^2 + g_w{}^2 + b_w{}^2} > \sqrt{r_u{}^2 + g_u{}^2 + b_u{}^2}$$

then: $$w - u = u$$

A difference calculation can be seen in Figure 10-21, the magnitude of the colour weight of shape A, the green colour is the lesser of the two, is closer to black in the RGB colour space, so is used for the intersecting area in the shape difference calculations.
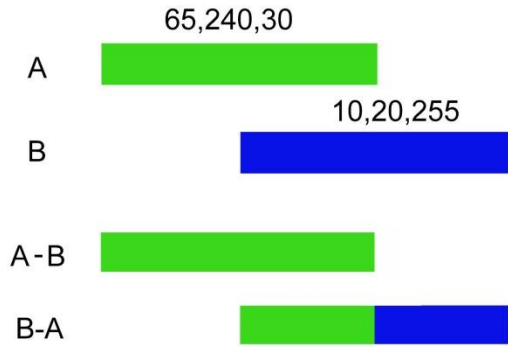
Figure 10-21: RGB weight difference calculation

The tile Figure 10-22 in shows the previous RGB tile from Figure 10-18 with a purple cylinder subtracted, cylinder shown in a transparent shadow to demonstrate where it has been subtracted from position, although would not actually be in the design. In this design only the green and dull purple colours are closer to black and so remain the original colour, the rest take on the deep purple of the subtracted cylinder.
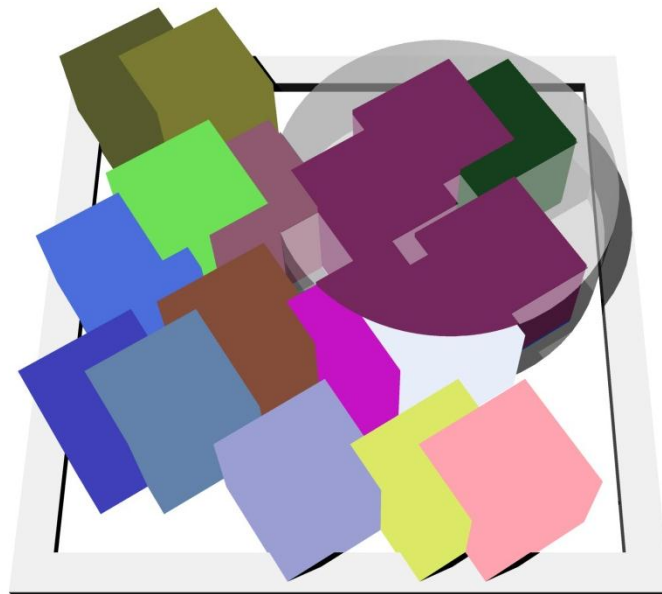
Figure 10-22: Tile design showing an RGB difference calculation

A third colour system that can be readily used and converted to RGB in Grasshopper is the HSL colour system. HSL stands for hue, saturation, luminosity and was developed as different way to manage RGB colours for screen based use [9]. The numerical values therefore relate to other colour attributes rather than primary colour values, allowing the designer to experiment and control these attributes more directly. HSL can be represented as a cylinder shape, where the hue values are the angular dimension, with red at 0 degrees, green at 120 degrees and blue at 240 degrees. The vertical access is variation of luminosity, the horizontal plane is variation in saturation. These values are interpreted by the system into RGB colours for display on screen.
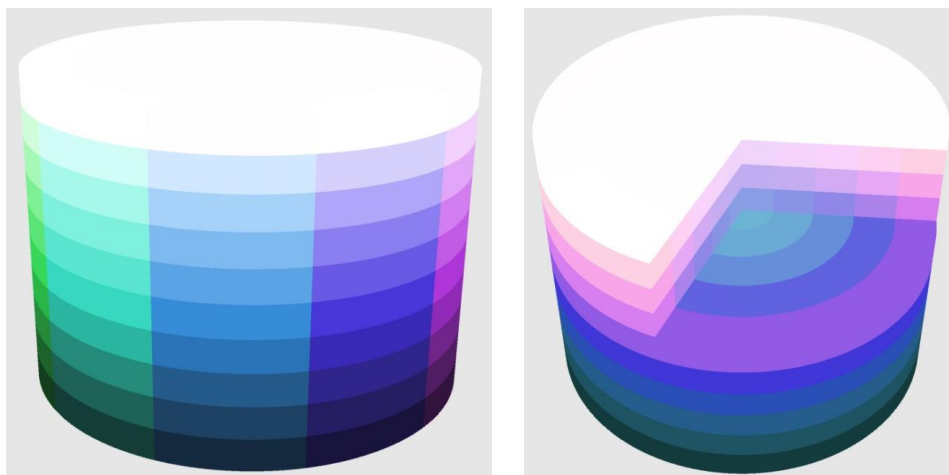
Figure 10-23: Cylinder Representation of HSL Colour system

The HSL system has three uncouple channels with finite values, so a system similar to that presented in section 10.5 for CYM colour weights could be applied here. However the HSL colour has the strength that the designer can control a one or more of the attributes distinct attributes rather than primary colours. For example the designer may wish to manage the colours in terms of saturation, keeping the hue and luminosity values at a suitable constant, a weights system now follows to demonstrate this possibility.

A colour weight addition calculation that isolates saturation values could be used so when:

$$u_s < v_s$$

then $$u+v = v$$

Alternatively if $$u_s > v_s$$

then $$u+v = u$$

where u_s and v_s are the numerical values of the HSL colour saturation channel. A colour weight difference for the same scheme could be defined:

$$u_s < v_s$$

then $$u-v = u$$

Alternatively if $$u_s > v_s$$

then $$u-v = v$$

An example of such calculations can be seen in Figure 10-24, shape A has a green colour weight which has a smaller saturation value than shape B, so in the addition operation the blue colour weight of shape B dominates in the intersected shape. In the subtraction operations the reverse is true, the intersected shape inherits the less saturated green colour weight of shape A.
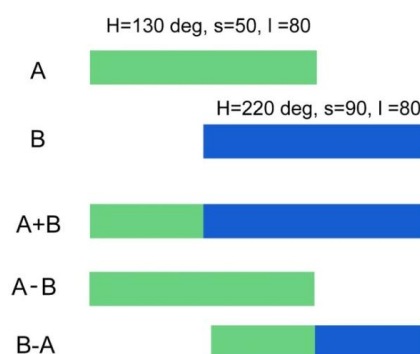
Figure 10-24: HSL weight calculations

To define a product for this colour system a way of finding a colour value that contains a part of both parent colours is required, in this case the saturation values can be averaged to give a mid-range value for the new colour weight. Logically a product calculation should produce a new colour, so the hue and luminosity values are also require calculation.

One way to do this would be to defer to a shape ranking system, whereby the new shape takes on the hue and luminosity of the higher ranked shape involved in the transformation.

For shape A with weight **u** and shape B with weight **v**:

$$\mathbf{u}.\mathbf{v} = \mathbf{H}(\max(r_A, r_B)), \mathbf{S}=(u_s, v_s)/2, \mathbf{L}=(\max(r_A, r_B))$$

where r_A is the rank of shape A, r_B is the rank of shape B, u_s is the saturation value of weight **u** and v_s is the saturation value of weight **v**.

Figure 10-25 shows such a calculation, the first result showing the outcome when shape A has a higher ranking than B, so the new colour assigned to the intersection in the subtraction operation has shape A's hue and luminosity values. Below this the same operation but with shape B ranked greater than A, the new colour inherits hue and luminosity values from shape B's colour weight.
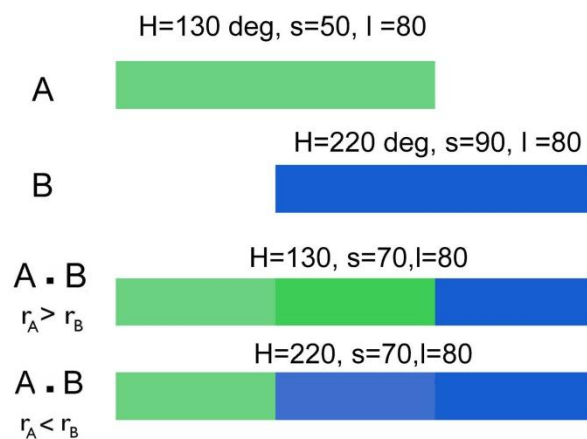
Figure 10-25: HSL colour weight product calculations

In some cases if the saturation is the focus of the weights system it may be likely that the hue and luminosity values are constant in each weighted shape the designer introduces into a design, in which case using a ranking system or some other supplementary system is not necessary. This example shows a system that isolates saturation values, however the same procedure could be carried out with the luminosity values. Hue values in the HSL system are a different case and are examined in the next HSL weight system.

10.8 A second HSL colour weight system

Hues in the HSL colour system are positioned in a wheel shape, the colours change in hue around the wheel, the three primary colours of red green and blue (from the RGB system) are positioned at 120 degree intervals. Although the numerical values of 0 to 360 could be taken as some kind of hierarchy for finding the maximum and minimums to calculate the result of weight additions this would be incongruous to the character of this particular colour space as hues are modelled as different but equal by the geometric form it takes.

A modular stepping system, similar to the one presented by Knight [61], could complement the relationship between hue values in the HSL system. Knight suggested that colours in a design could be defined by referencing a modular scale of constant hue and variable lightness, the colour of the shape stepping along this scale with each rule application. We can remap this as moving through different hues in a polar stepping system for the HSL system, so there are no minimum or maximum values for the hue channel. The saturation and luminosity values could also be subject to modular stepping operations, but with limits at 0 and 100.

Knight [61] uses coloured shape rules to subdivide shapes with coloured areas, the colour in the rule has no specified ranking or value, but this area pushes other coloured areas it transforms a step along the reference colour scale.

This is different from other approaches as instructions for weight results are embedded in the shape rules, rather than being a separate calculation the result of which is then applied.

Fundamentally it more closely resembles descriptions of making, craft and tool use, where material properties influence the results of transformations and are ingrained in the tools and materials. The instructions could refer to the changes in colour of any new shapes produced by transformations, in intersections as the previous weight systems have defined, but also in any shapes on the right hand side of a rule.

An extension of Knight's system was discussed in section 9, demonstrating how instructions for modular stepping weight calculations could be embedded in shape rules. This extension in now shown in practice using the HSL colour space as a basis.

In Knight's [61] approach overlapping coloured areas created in a transformation are given a new colour, calculated by referencing the original colour on a scale and stepping to the next colour, the colour in the rule has no specified value, it instructs where weights are to be recalculated.

If rules were to contain specific colours then a method of ascertaining which of the colour weight is to be used and stepped and which is disregarded in required. So for shape A with weight **u** and shape B with weight **v**, if:

$$\mathbf{r_A} > \mathbf{r_b}$$

then $$\mathbf{u + v = (u_h + x, \ u_s + y, \ u_l + z)}$$

where **x** is the step increase chosen by the designer for the hue channel, **y** a step increase for the saturation channel and **z** a step increase for the luminosity channel. Also $u_s + y$ and $u_l + z$ have limits of 0 and 100.

Figure 10-26 shows an example of a calculation where the step increase in an addition calculation is +20 degrees to the hue channel.
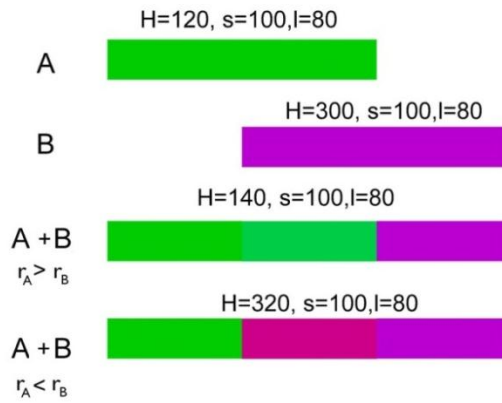
Figure 10-26: HSL stepping weight addition calculations

When shape A has a higher ranking than B the colour weight of shape A has the step applied and is assigned to the new intersection shape. The reverse scenario, where shape B has a higher ranking than shape A, the new colour weight for the intersection is the colour weight of shape B with the step value added.

Shape ranking systems have been discussed in section 9.3, the designer can choose how to rank the shapes for this approach. The tile design in Figure 10-27 uses a simple chronological ranking system, new cubes added are ranked lower, intersections from addition operations inherit the weight of the cube already present in the design with 20 degrees added to the hue channel value.
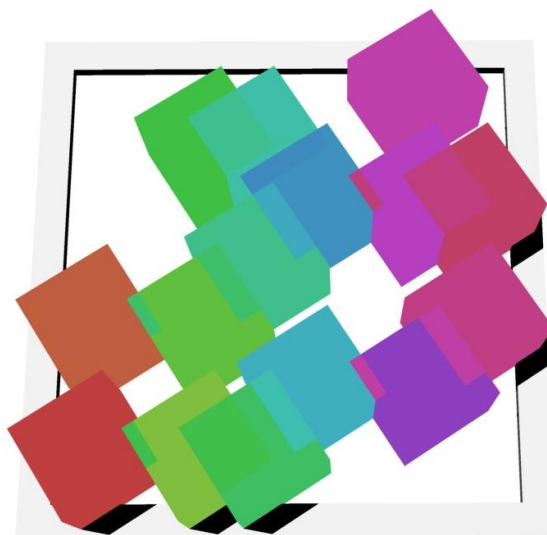
Figure 10-27: Tile generated using HSL weights with stepping additions

To adhere to the structure of previous schemes presented in this thesis a definition for calculating the product of two HSL hues for a stepping weights system can be set. This could come into play when shapes have equal ranking, for instance shapes with different weights that are added to the design at the same time but have an overlap. The intuitive choice for this would be to find the average value between each of the two values of each channel, like most of the other systems discussed, for u and v:

$$\mathbf{u.v} = (u_h+v_h)/2,\ (u_s+v_s)/2,\ (u_l+v_l)/2$$

Figure 10-28 shows a product calculation using this definition. The result of taking an average polar position between the two colours delivers a hue the appears as a kind of compromise between the two, although not the equivalent of mixing these two hues as paint, which would produce a brown hue.
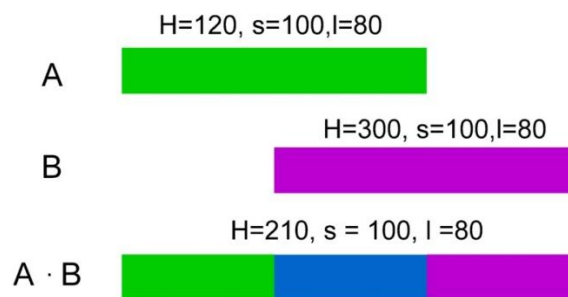
Figure 10-28: HSL product calculation for stepping weights system

Figure 10-29 shows a tile design generated using product calculations like this for intersections, the two hue values are averaged, giving a numerical value for a colour midway between them on the hue colour wheel, luminosity and saturation have been kept constant, at a value of 50 for every cube.
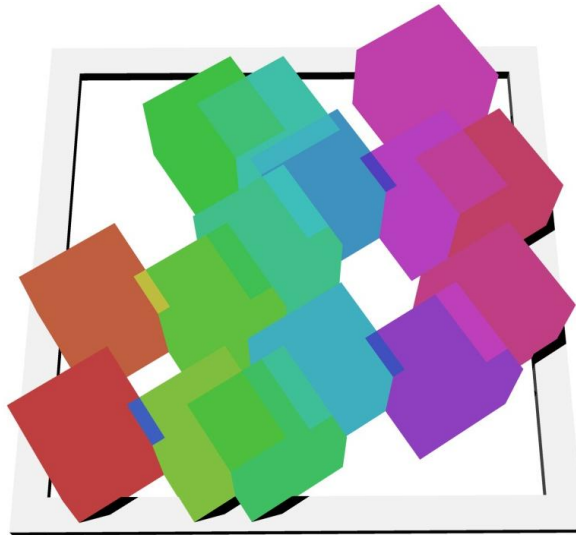
Figure 10-29: Tile design using HSL product calculations

This tile gives a wider view of the results of this calculation, it can be seen that the more disparate the two parent hues the less the product colour has in common visually with them, as can be seen in the red and green cube overlap in the bottom left hand corner, a strong blue colour has been calculated, which visually does not seem to have much relation to the two input colours.

The difference calculation for a modular stepping system for HSL colour could reflect the addition calculation by subtracting a step from the colour of the shape that will remain in the transformation. Figure 10-30 shows such a calculation, when shape B is subtracted from A the green colour weight of A is stepped back 20 degrees and applied to the remainder shape, when shape A is subtracted from B the purple colour weight of B is stepped back 20 degrees and applied to the remainder shape.
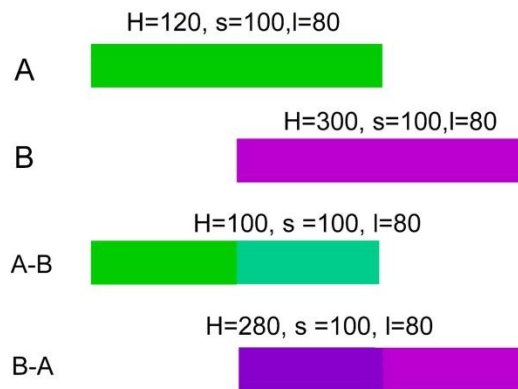
Figure 10-30: HSL Difference Stepping Calculation

For these examples additions have been representative of moving clockwise round the wheel and anti-clockwise for difference. There is no reason why the designer could not choose a reverse system. Limits or allowing values to wrap around on all the channels is another discretionary design decision. Again the designer-maker can take this colour management tool and use it or transform it to generate outcomes they find useful.

10.9 Segmenting colour systems

The previous weights examples make use of the full colour spectrums of three of the colour systems available to use in this particular computational making design exploration. Colour systems are part of the tools for colour management, a set of relationship rules. Like the rules for calculating colour weights in shape interactions, the colour spaces can also undergo transformations to produce a new set of colour weight rules or tools.

One way to do this is to segment colour spaces by applying maximum and minimum values for attributes and limiting the number of colours by modularising an existing colour space. This produces limited colour spaces that still have numerical values relating to a standard colour space and can be used in the ways previously explored, using calculations with operations such as adding, subtracting, averaging and stepping. For instance, Figure 10-31, shows such a segmented, modular colour space based on the CYM system. In this system Cyan values run from 0 to 100, Yellow from 25 to 75 and magenta 0 to 50, with four modular steps in

between, creating a smaller colour system that can be used for calculations with rounding and limiting to restrict the colour weight results to the selected colours.
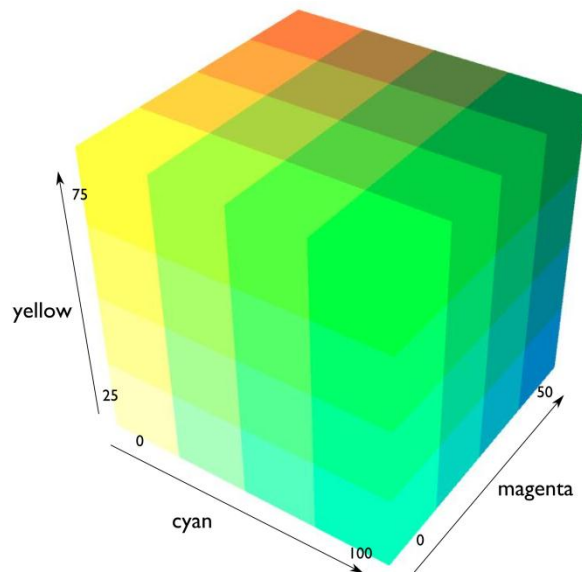
Figure 10-31; Segmented, Modular Colour System based on CYMK values

Segmenting in one possible transformation the designer can make on a standard colour space to produce bespoke and possibly creative colour outcomes in a computational making design process using weights and ink coating fabrication technology. The transformations can be experimental or be informed by other aspects of the making process, such as utility and aesthetic aims

10.10 Colour palettes

A more dramatic transformation of an existing colour space is to not only limit and modularise the selection of colours but also to specify new relationships between them producing tailored colour palettes that can be used for weight calculations.

Colour spaces are ranges colours of positioned with a geometric form to define the relationships between them. A designer could select a number of colours and arrange these in a geometric form, the relationships between the colours are synthesised by the designer. Such a colour palette can be used as a basis for colour weight calculations to determine the colours

of shapes resulting from shape transformations in ways that are sympathetic to their geometric relationship, Figure 10-32 shows and example of a colour palette, a range of colours without obvious scaled relationships corresponding to their positions arranged in a cube form. A numerical system to use for weight operations, such as addition, subtraction, averaging or stepping would accompany the palette which would relate or convert the results to colours from one of the available standard colour systems such as CYMK, RGB or HSL.
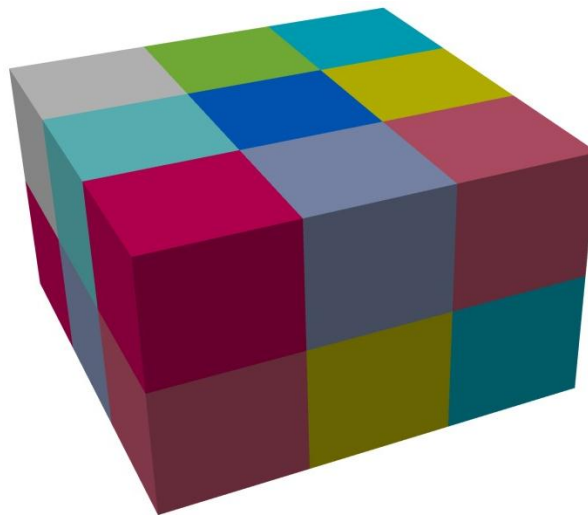
Figure 10-32 Bespoke 3D colour palette for a weights system

This approach could be used when the designer-maker requires a specific colour scheme, in scenarios such as to fit an interior design or brand colours. A stepping scale, like the second HSL weights system, of unrelated colours could be used to signify or even alert the designer certain changes in a shape through successive rule applications, for example a to alert that the shape has is heading towards or reached some kind of limit caused by transformations like scaling operations causing shapes to become too large.

10.11 Printing results

Some of the tiles from the design experiments were printed on a Z-Corp printer to allow comparisons with the colours on screen and in the physical object. Figure 10-33 shows a render from Rhino alongside a photograph of the same tile printed, these visual

representations on the printed page and screen will be different from the originals, but will show that the colours are different in each. For the author comparing the view on screen with the printed object demonstrated differences caused by the conversions the colours underwent from generation to print, red hues appear pinker in the finished print, greens lighter and hues less saturated than the on screen colours.
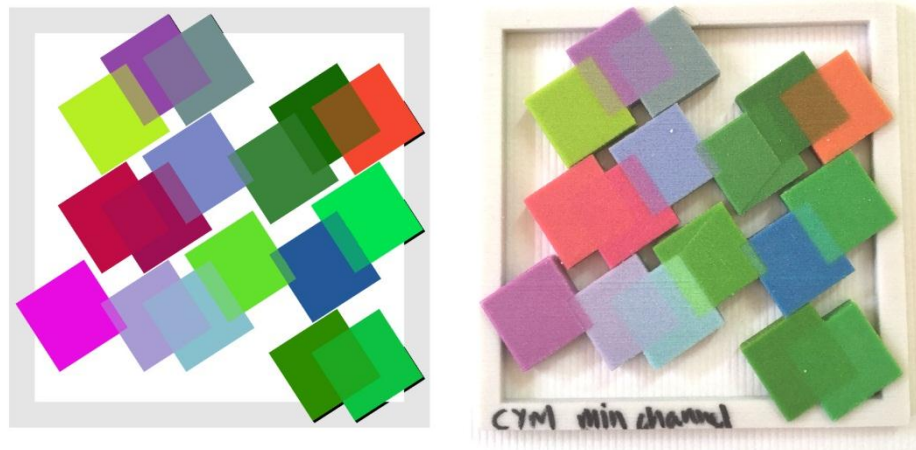
Figure 10-33 Tile generated with CYM values alongside photograph of printed version

A second tile, generated with RGB colours was also printed, the comparison between this and the rendered version is shown in Figure 10-34, again the colours the reader will view on the page are different from those being assessed due to extra conversions by the camera and for printing on paper. For the author, comparing the onscreen colours with the printed object, the colours again had some differences, visually the hues of the colours seemed fairly close, what was lost was the brightness and saturation of some of the colours.

On comparing the printed tiles each had opposite advantages and disadvantages, the CYM tile colours were more saturated and vivid, but the hues appeared to be further from the on screen representations. The RGB tile had better matched hues, but bright colours appeared less saturated and pastel-like in the printed tile.

Figure 10-34: Tile generated with RGB values alongside photograph of printed version

For design processes the maker is likely to do some printed tests to confirm colours for use in computational tools. With this in mind the author built three Grasshopper tools to generate representations of the three colour spaces for printing on the Z-Corp printer. Figure 10-35 shows a HSL cylinder representational model for print, around the wheel are twenty hue values from 0 to 1, the outer ring or colours shows saturations of these at 1, the inner at 0.5. Each level in the z axis gives a step of luminosity, ranging from 0.2 to 0.7, with 0.5 in the middle, 0 and 1 have been omitted as these appear completely black and completely white respectively.
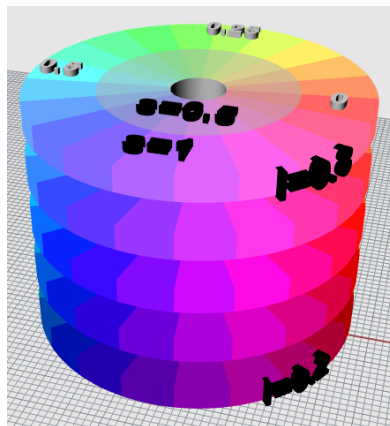
Figure 10-35 HSL space Z-Corp colour printed representation

Figure 10-36 shows the RGB colour space in 5x5x5 modules, again to give a guide of how the colour values are interpreted from Grasshopper through each conversion, through to the finished print.
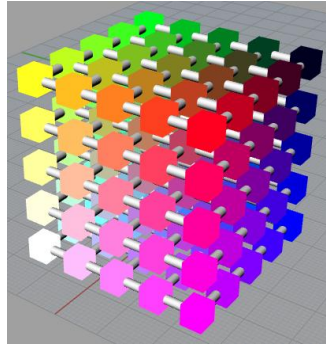
Figure 10-36 RGB space Z-Corp colour printed representation

Finally a cube of colour 5x5x5 colour modules generated using the CYM tool in Grasshopper is shown in Figure 10-37.
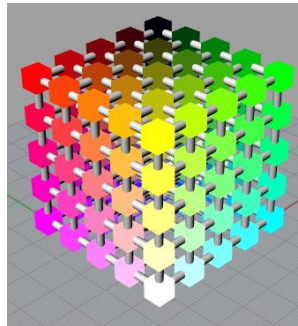
Figure 10-37: CYM space Z-Corp colour printed representation

Such models can be printed by the designer-maker on the printer they wish to use for the designs, providing three dimensional colour reference swatches. They would aid the designer in making decisions about segmenting colour spaces and ensuring or checking how colour values in the digital realm will be interpreted by the printer they plan to use.

10.12   Applying colour to shapes

The Z-Corp colour printer works by coating the surface of a bonded gypsum print with ink, so for printed shapes the outer planes are coloured, not the solid shapes; if they were cut the

inside would be white. Each mesh face is assigned a colour or gradient by digital representation to instruct the printer.

This means in the computational part of the design process the designer using a three dimensional shape grammar as part of their design process has to decide how to computationally model the colours on the shapes. Assigning each face of a three dimensional object a colour is one approach, that would work with this kind of printing where the colour is a coating. Having multi-coloured shapes could be a desirable attribute for a design. The designer then only has to calculate the colour weight of any areas where two shape faces share the same plane, as in Figure 10-38, where the two intersecting cubes share the same plane on the top face and so the intersecting area. How often this kind of overlap is likely to happen depends on the type of shapes and how they are instructed to interact.
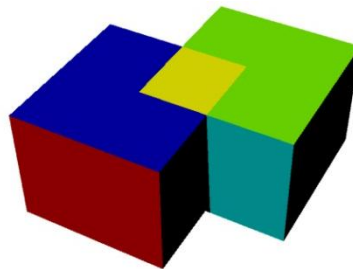
Figure 10-38 Multi-coloured cubes intersecting

The designer could choose to digitally model shapes as having a solid colour all the way through and allowing a final resolution of surface colours before printing. This approach may be useful if later subtractions are applied to the design. For example two 'solid' coloured cubes are shown overlapping in Figure 10-39, theoretically for Z-Corp colour printing no calculation is required for the colour of the intersection as it is not visible.
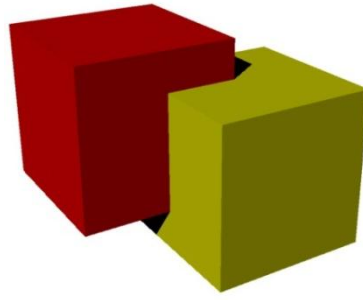
Figure 10-39: Solid coloured cubes interacting

However if there was a situation in the making process where the designer wished to remove parts of the shape a colour for overlapping area would need to be calculated, giving a result similar to Figure 10-40, where the cubes from Figure 10-39 have undergone a subtraction of a sphere, revealing a face of the inner part of the cubes.
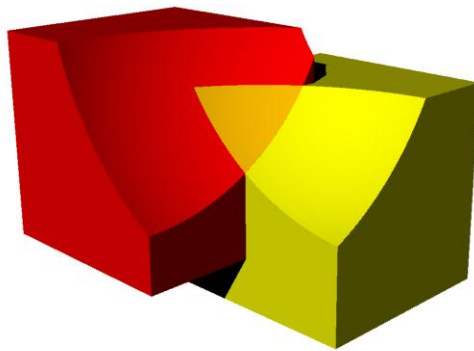
Figure 10-40: Solid Coloured Cubes with Sphere Subtracted

The third option that may be appropriate with Z-Corp colour printing is to assign the calculated colour weight of the two shapes to be assigned to both shapes, allowing them to union into one solid shape. To return to the cubes in Figure 10-39, if orange has been calculated as result of the weight addition the cubes become one shape with this colour, as in Figure 10-41.
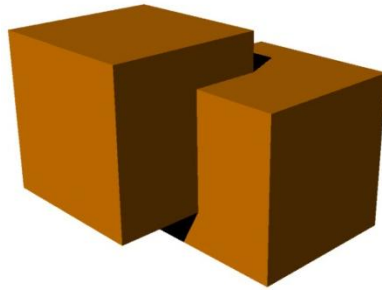
Figure 10-41: Solid coloured cubes unioned and both assigned new colour

10.13 Embedding

In shape grammar new shapes resulting from transformations follow embedding rules; shapes with the same weight that share planes or boundaries become joined or subsumed into one another as whole shapes.

If two weighted shapes intersect in a transformation the new shape created will be removed from a shape with a lesser ordered weight. In a colour system using shape ranking, higher ranked shapes would retain their original form in an addition operation, whereas overlapped, lower ranked shapes loose parts and become new shapes. For example the original cylinders 1, 2 and 3 in Figure 10-42, (taken from a previous example in Figure 9-7) become cylinder shapes with arc shapes removed after the addition of each consecutive shape in the design, only cylinder 4 remains a cylinder as the last shape, they can be seen moved apart in Figure 10-43.
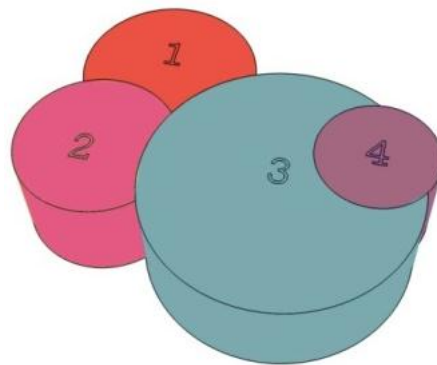
Figure 10-42 Cylinders design with chronologically ranked shapes
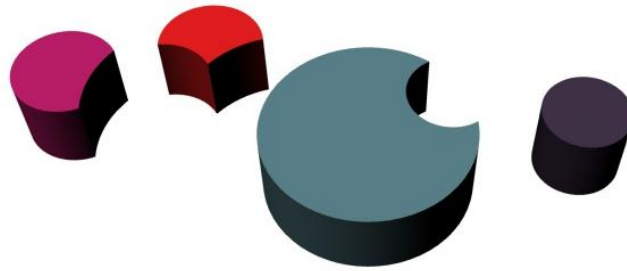
Figure 10-43: Shapes from previous figure

Embedding of weighted shapes can lead to the fracturing of the original shapes. If further rules are required to identify and or transform certain shapes, for instance the cylinders, shapes numbered one to three no longer exist in the design as cylinders. This could cause frustrations for a designer wishing to use weighted shapes in their computational making process while retaining the integrity of chosen shapes.

In a computational making situation an alternative approach can be used because objects created in a CAD environment can occupy the same space until Boolean operations are applied to them. In the design experiment with the ranked cylinder shapes, it was possible to perform Euclidean transformations in the Rhino environment on the cylinders while the Grasshopper tool updated a design with the shapes and weights resolved. This demonstrated that an approach of resolving weights at the end of a design exploration with overlapping weighted shapes is possible and may be preferable to avoid shape fracturing and in a computational environment a generative tool can rapidly recalculate each outcome while giving the designer the opportunity to manipulate whole shapes.

In a physical making situation embedding is related to material properties. Some materials are easily subsumed into one another, such as liquids, where more solid material elements are arranged without loss of the original shape. In a digital environment the designer can choose how they want their design elements to interact. Thus the designer using shape grammar weights as a system for colour management in a computational making situation can choose to embed shape elements whenever it suits them in a design exploration.

10.14 What is a zero weight?

Knight and Stiny suggest that a '0' weight can be assigned to shapes in subtractive operations, and this constitutes the removal of a shape altogether, leaving nothing. This could be adhered to in any colour weights system for the computational making with an ink coating fabrication system examples previously presented.

In the CYMK colour space a value of 0,0,0,0 represents the absence all the inks. So in the case of printing onto a white material, such as the white gypsum powder used by the Z-Corp colour 3D printer, the colour of the object in this area is white, but is still and existent solid shape.

In the RGB colour space the colour of the 0,0,0 value is black, as it represents an absence of light. If RGB colours were used for weight representations and calculations in the computational phase of a design process but then converted to the CYMK colour space for printing, a shape with a zero weight would be a solid black shape in the fabricated object.

Alternatively the designer could choose a zero value to constitute the removal of all material and colour from and area in a three dimensional design. These examples from colour systems show that even assigning a zero weight to all subtractive shape operations requires further consideration, according to the properties being modelled.

10.15 Parametric colour weights

Stiny [106] and Knight [59] both suggest that weights could have parametric properties, but neither give specific examples. As has been shown colour in computational making is represented by colour systems that are built into the various software and hardware, represented by numerical values which lend themselves to parameterisation.

Section 9.3.3 of this thesis examined the possibility of parameterising shape rankings by using relations with shape attributes, such as size and position in a design. Colour weights based on digital colour systems could also be parameterised according to shape attributes such as size,

position, volume. For instance the saturation of a colour weight could be related to the volume of a shape, with greater saturation on smaller volumes, vice versa or some other mathematical relationship.

Parameterisation could also take place in the weights systems themselves. Modular stepping weights systems, such as the second HSL weight presented in section 10.8 could be parameterised. The numerical constant added to the previous hue value could be parameterised according to shape attributes. One example of this would be a weight system that links the volume of a shape to the number of steps the colour progresses along the weights system; a larger sized shape increases the colour in any overlap by a larger number of 'steps'.

10.16 A computational making process with colour weight tools for Z Corp colour printing

Taking the tools built for the previous design experiments the author wished to embark on a computational making process in order to investigate how weights could further a creative making process. The previous design experiments and weights schemas provided tools that could be co-evolved with new outcomes. Decisions on colour relationships, calculations, limits, zero weights and segmenting provide the designer with a flexible weights tool open to transformations like those seen in the first part of this thesis. Such transformations on tools can give rise to creative episodes and outcomes an initial framework is need to then manipulate, shape grammar weights can offer this for computational making with multi-material 3D printing. This design experiment looks how the previous weights definitions can be used as tools in a computational making design process.

The designer decided to shift the design goal to a smaller object more affordable to print, and easier to display. Vessels were selected to meet these criteria, but also provided a nod to one of the crafts long standing archetypes.

Reflecting on the previous experiments the designer wished to pick out some interesting tool features that had emerged through the definitions and try and translate these into interesting features for a design. The designer homed in on a particular characteristic of three dimensional shapes discussed in section 10.12, intersections between three dimensional shapes are hidden unless they share a plane, but can be revealed in the CAD environment by performing a Boolean difference operation to expose them to view.

Making the analogy between the hollow form of a vessel and a Boolean difference operation allowed the designer to develop a design idea – that the hollowed out part of a vessel could expose the shape intersections, creating and interesting feature in this area with a different pattern and colours contrasting with the parts showing the original shapes.

With this idea the designer returned to the Grasshopper tools, selecting the RGB product tile tool as a basis to develop a new tool through transformations. The RGB tool was selected as the author wanted to calculate secondary colours for the intersections, to emphasise the difference between the hollowed out area and the other surfaces. RGB product calculations, based on averaging each channel, had resulted in colours that appeared as if the two parent colours had been blended or combined translucent layers, which the designer found interesting and visually pleasing.

To ensure shape intersections were not visible on the other surfaces the first thought by the designer was that the cubes from the tile designs would become cuboids with varying heights. Serendipitously a discovery was made in the Grasshopper tool, the readymade Grasshopper module used to draw the cubes in the design had an option to enter a truncation value. Exploring this with different values the designer happened upon a shape that could be arrayed with hidden intersections, see Figure 10-44, flat on top but with prisms like shapes that would overlap when place close enough.
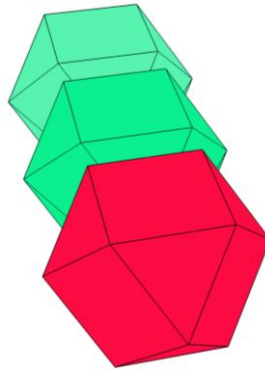
Figure 10-44: Shape found to form the basis of vessels

Finally a Boolean difference operation was added to the tool, to remove a flattened sphere to create the bowl shape in the vessel design. Figure 10-45 shows the first bowl generated with the new tool, a colourful and unusual decorative bowl, which was then printed on a Z-Corp printer. The intention is that the bowl exhibits characteristics of other materials – solids with the uncanny ability to merge and blend colours but rendered in a solid opaque material, creating surprise and delight.
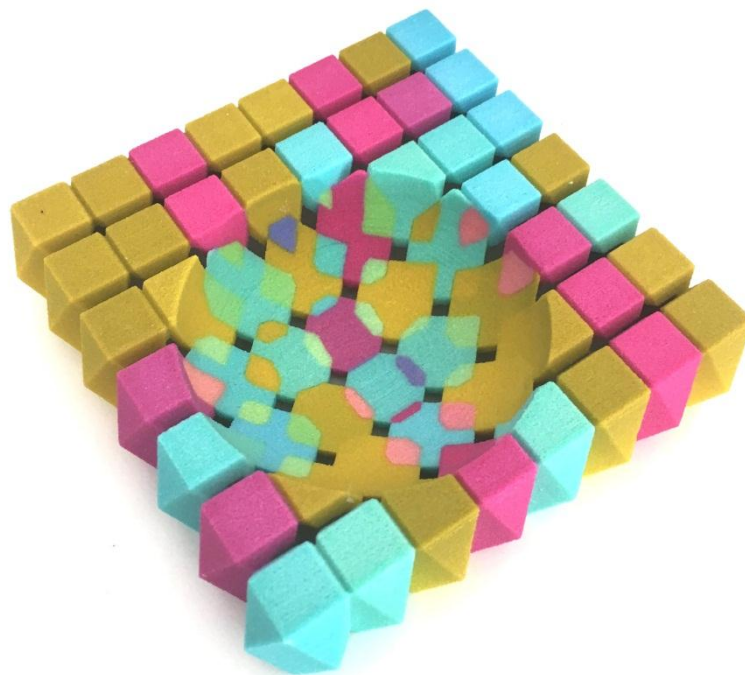
Figure 10-45: Novel bowl designed with shape grammar weights tool

This addition design experiment demonstrates that weights are a useful computational making tool, they provide a way of generating objects but have enough flexibility to allow transformations and reinterpretations, giving a designer-maker the chance to use them creatively in different computational making scenarios.

11 OBJET CONNEX CASE STUDY

In addition to the Z-Corp colour printing, another 3D printing technology is currently available that allows objects with variable properties to be printed. The Objet Connex is a 3D printer that can combine two or three different resins with different properties in one printed object, and by mixing these in different proportions produce a further array of secondary materials. A range of plastics are available, with various transparencies, colours and material properties which can all be blended with one another.

This system has some notable differences from the Z-Corp ink coating system. Firstly different materials exist as joined solid shapes, not just as a surface treatment. The range of materials has multi-properties and behaviours, one print can contain materials with gradations of colour, flexibility and transparency. Therefore this 3D printing system is likely to require a different dedicated weights system, so a series of design reasoning and experiment was carried out to investigate what these may be.

Parts of this work was developed in collaboration with Iestyn Jowers of the Open University and has been published in a papers at the Siggraph Asia 2014 conference [71] and the journal Graphical Models [72], in particular sections 11.1, 11.2, 11.4, 11.5 . Since this publication parts of this work has been revised by the author as more knowledge was gained from other design experiments and reasoning to improve the definitions.

This section develops some weights systems based on shape grammar weights as tools for computational designer-makers to use or transform in order to generate designs for multi-material and property 3D printing, in systems where parent materials are mixed in varying proportions to create a range of materials with gradations of various properties.

This has been done by carrying out some design experiments focussing on two of the available materials, a hard white plastic material called *VeroWhitePlus* that can be mixed in different proportions with a soft rubber-like black material called *TangoBlackPlus* to produce a range of

composite materials by the Objet Connex 3D printing machine, a promotional sample print produced by Objet is shown in Figure 11-1 showing the range of resulting materials. As the proportion of *TangoBlackPlus* increases the Shore rating decreases, the tensile strength decreases, and the elongation at break increases; materials become softer and more flexible as the proportion of *TangoBlackPlus* increases and closer to black in colour. The result is that objects which display different physical behaviours can be 3D printed.
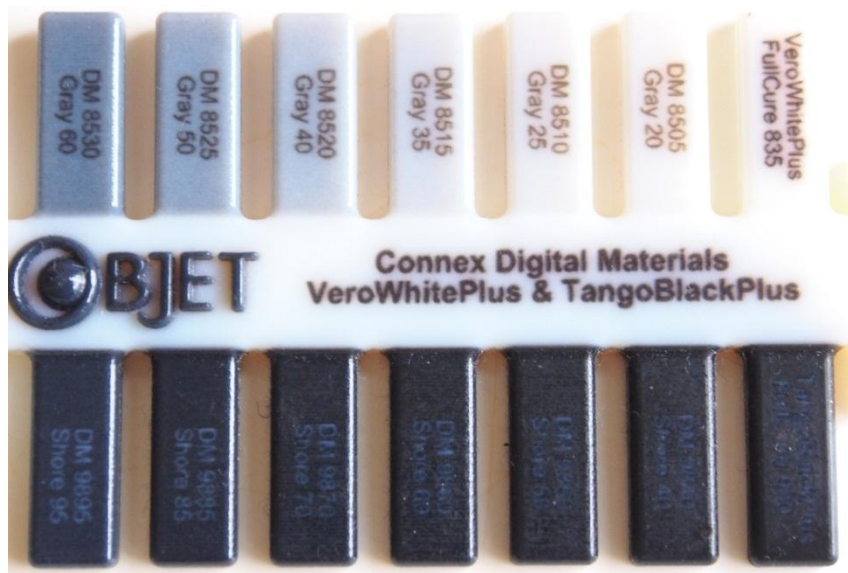
Figure 11-1: Object printed sample combing VeroWhite and VeroBlack materials

In practice when setting up files appropriate for printing through a bureau service, the composite materials that are produced by combining *VeroWhitePlus* and *TangoBlackPlus* are limited to the fourteen discrete examples illustrated in Figure 11-1. However for the computational design experiments an allowance of any percentage proportion has been allowed, as in theory any proportion of the two materials is possible in one shape.

Z-Corp colour printing produces different coloured surfaces in one print by using CYMK inks, mixed in varying amounts, each primary ink is given a number between 0 and 100. As demonstrated this resulted in the development of three channel weights systems to enable the management and calculation of colours in a printed design. However the colour on such a 3D print is a surface treatment on a homogeneous material, and does not constitute the actual

shape, it is a weight system for a shape attribute. The Objet Connex produces objects where each part is a given material all the way through, so different considerations are required.

The Objet Connex has two or three primary materials, similarly two or three channels to be considered in the weight system. However, unlike the CYMK colour system, the channels are proportionally dependant, as the amount of one increases the other decreases, with the result of increasing or decreasing the flexibility of the composite material. The behaviours of an object printed this way with have different physical behaviours dependant on its shape, size and materials. Therefore a different weights system is required to model this type of 3D printing as the relationships between the materials are different, the way they relate to shapes is also different and the way they behave may be variable, and as a result have different design possibilities.

An initial way of defining this system for weight calculations is to model the system as a single numerical value, as the percentage of one of the primary materials in the composite material. For example w is assigned a value from 0 to 100 to reflect the percentage of *TangoBlackPlus* in the composite. Formally, w is defined as

$$\{w \in \mathbb{N} : 0 \leq w \leq 100\}$$

This means that when $w = 100$, the material is black, very soft and very flexible; when $w = 50$, the material is grey, semi-soft and semi-flexible; and when $w = 1$, the material is near-white, very hard and very rigid. As with colour there are different ways to define a weights system, the system can be tailored to suit the requirements of the designer's task at hand. Some possible approaches that may be relevant in computational making processes are now discussed, weights for this kind of 3D printing are related to the properties an object will have and the approach can be to work with these in mind as the rules are defined.

As described the Objet Connex and can print objects with varying flexibility, therefore the designer may wish to use a weights system that models the flexibility of areas of an object. To include *w* in a shape computation it is necessary to define a relation between different weight values, as well as the operations of sum, product, and difference. One way to do this is to base the system of Stiny's weight system of using the maximum and minimum weights as the result of the operations with an emphasis on the flexibility of shapes as follows.
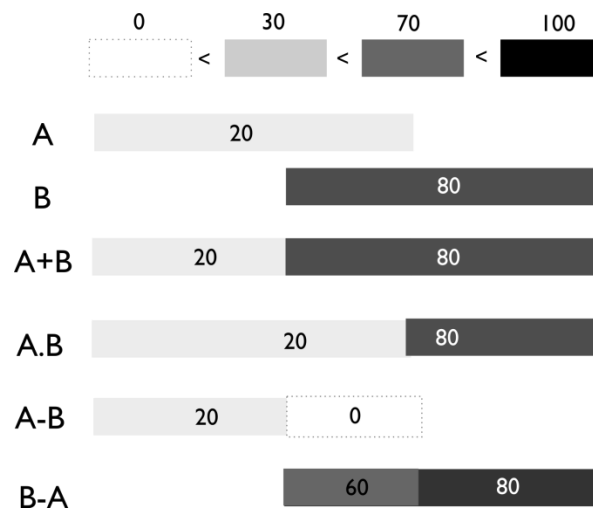
Figure 11-2: Connex weight for flexibility calculations

The top row of Figure 11-2 shows an illustration of the visual appearance of certain numerical weight values from 0, when a shape with this value would be constituted of 100% *WhiteVeroPlus* and is modelled as being lesser than a shape with value 100, where the shape is 100% *TangoBlackPlus* and, completely black and most flexible. Here, the relation is defined as a linear total order, so that stiffer materials are embedded in, and subsumed by, flexible materials. So, given two weights *w* and *u*, the relation between the weights can be defined as:

$$w < u,\text{ if the numerical value of w} < \text{numerical value of u}$$

This states that *w* is a part of *u* if the numerical value of *w* is less than the numerical value of *u*. Intuitively, applying the sum operation should give a material that is of a flexibility that subsumes both *w* and *u*, and the result would be the more flexible of the two. So as in Figure

11-2, when shapes A and B, with weights **w** and **u** are added the sum operation to find the weight of the intersection shape is defined as:

$$w + u = max(w, u)$$

Similarly with the attribute of colour previously explored, the designer may want overlapping areas to take on a the product of two weights, in this case the operation should give a material that has a flexibility that is common in both **w** and **u**, and the result could be the more rigid of the two. So in Figure 11-2 the combination of shape A and B with weights **w** and **u**, the product operation is defined as:

$$w \cdot u = min(w, u)$$

The difference operation should give a material that has the flexibility that remains in **w** after **u** is removed, so the result is a material more rigid than both **w** and **u**. In Figure 11-2, the result is given by the arithmetic difference with a minimum value of 0, where a shape is wholly consisted of *WhiteVeroPlus* and is defined as:

$$w - u = max(w - u, 0)$$

Figure 11-3 demonstrates a shape addition using this system, two surfaces are equal in size, but have weighted stripes running orthogonally, so that when they are added the stripes create a checker-board pattern, the result is a more complicated arrangement of weights, with the more flexible, darker weighted shapes dominating the rigid stripes.

Figure 11-3: Shape Addition with multi-material planes

Figure 11-4 shows the product operation, and the result is a more complicated arrangement of weights, with the more rigid stripes dominating the flexible stripes.

Figure 11-4: Shape product with multi-material planes

In Figure 11-5 the difference operation is applied to the same weighted shapes, and the result is a checkerboard of weights, with areas appearing white, made up entirely of WhiteVeroPlus, where subtractions have resulted in values of 0 or less.
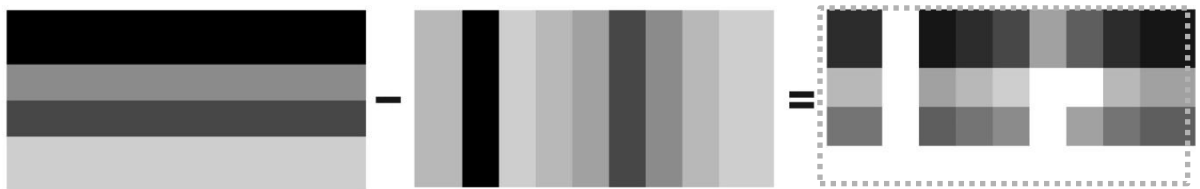
Figure 11-5: Shape Difference with multi-material planes

The shapes used in this example were printed on the Objet Connex. As expected the darker areas containing more TangoBlackPlus are more flexible and allow greater bending along theses strips, as can be seen in Figure 11-6 and Figure 11-7. The result is a textile like object with variable flexibility.
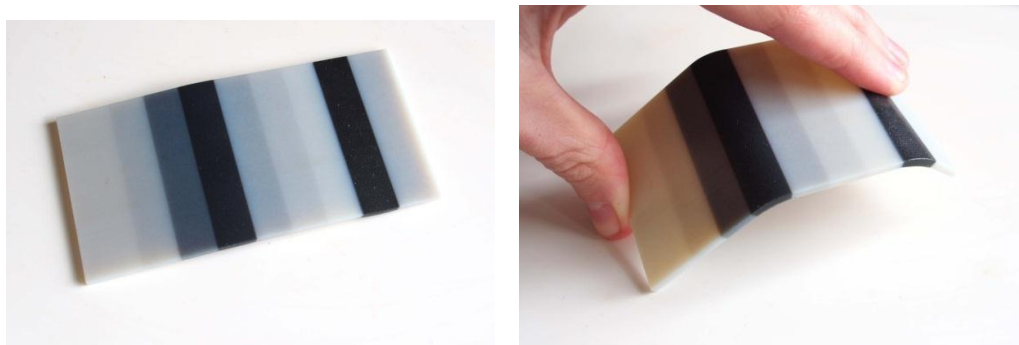
Figure 11-6: Vertical stripes printed weighted shape
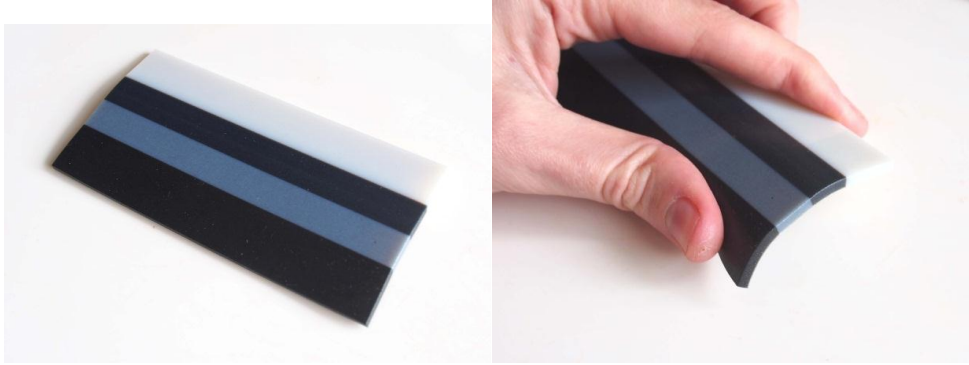
Figure 11-7: Horizontal stripes printed weighted shape

The weighted shape calculated from performing an addition calculation with this first system was also printed. The result is an object that can bend horizontally and vertically, in the same ways the two original shapes could bend. In this case the weight addition provides an increase and combination of flexibilities. This could be useful for generating objects that reconfigure in different ways, allowing extra capacity bending where required but maintaining rigidity in other areas.

Figure 11-8: Weighted Shape from addition calculation

11.2 Weights system modelling rigidness

The designer may wish to model the rigidness of an object, that is as shapes are added rigidness, or the amount of *WhiteVeroPlus* is increased in each area with the product and subtractive calculations corresponding to this preference also. If the designer wishes w to model the rigidness of a composite material, then the relation and operations defined over the weight could reflect this by inverting the previous system, and the relation and operations could be defined in a similar manner.

However in the interest of exploring other possibilities a different approach to modelling rigidness now follows. Figure 11-9 illustrates the relation and operations applied to shapes A and B with weights w and u, the top row showing an illustration of the ordering of materials and the associated numerical values for the weights, where 0 is flexible and completely constituted of *BlackTangoPlus* and less than 30, 70, 100, values which relate to materials with increasing proportions of *WhiteVeroPlus*.
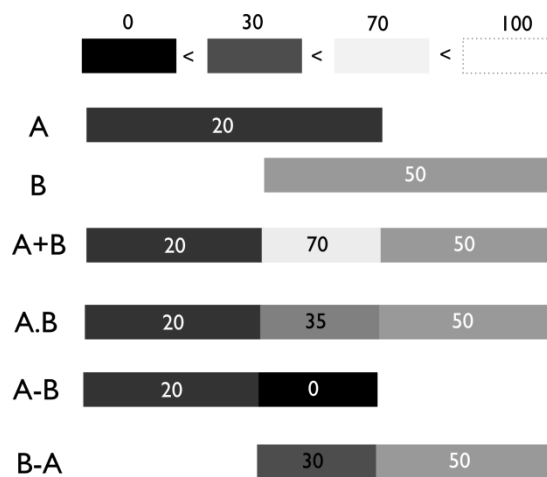
Figure 11-9: Shape operations on weighted shapes modelling hardness

This time the relation is defined as a linear total order, so that soft materials are embedded in, and subsumed by, hard materials. Given two weights *w* and *u:*

w < u, if the numerical value of w < numerical value of u

Applying the sum operation should give a material of hardness greater than *w* and *u*, and the result is their arithmetic sum, with a maximum value of 100:

w + u = min(w + u, 100)

As Figure 11-9 shows, the addition of shape A and B results in a sum total of the two parent weights being assigned to the intersection shape.

This time the product operation results in a material that has a hardness that is between both *w* and *u*, and is defined as the arithmetic average of the two:

$$w \cdot u = \tfrac{1}{2}\,(w + u)$$

The difference operation should give a material that has the hardness of *w* after *u* is removed, and the result is a material softer than both *w* and *u*, given by their arithmetic difference with a minimum value of zero:

$$w - u = \max(w - u, 0)$$

Figure 11-10 shows weighted shapes added with using this rigidity centred approach, it can be seen that the result tends towards lighter shape parts as it become composed of greater proportions of *WhiteVeroPlus* and becomes more rigid.

Figure 11-10: Weight system for rigidity addition example

Figure 11-11 shows the calculated product of the same two weighted shapes, the result, as expected appears to be a compromise between the two, each shape weight tending towards a mixture of the two parent materials than that of the original shapes. As the product finds the average of the two original weights, the numerical results have been rounded to one of ten steps between 0 and 100 of TangoBlackPlus, towards the numerically higher and visually lighter material step, to restrict the shape to one of the ten original modelled weights or combinations of the two materials.

Figure 11-11: Weight system for rigidity product example

Figure 11-12 shows the result of a difference calculation on the weighted shapes, the result tending to dark, black flexible weights on the shapes as rigidity is removed from the shape by the other.

Figure 11-12: Weight system for rigidity subtraction example

11.3 Weights tool incorporating material density

As Objet Connex materials are printed as solid parts another material property could be modelled in a computational making process, that of density. A shape can contain a proportion of the two materials but also a proportion of empty spaces, creating a second component that is also likely to affect the behaviours and properties of the printed object.

For example Figure 11-13 shows a set of possible materials and relationships for the Objet Connex, using three steps of blends of the *WhiteVeroPlus* and *BlackTangoPlus materials*, however a second dimension to these materials is achieved by printing shapes with increasingly less empty square spaces, increasing the density of printed material.
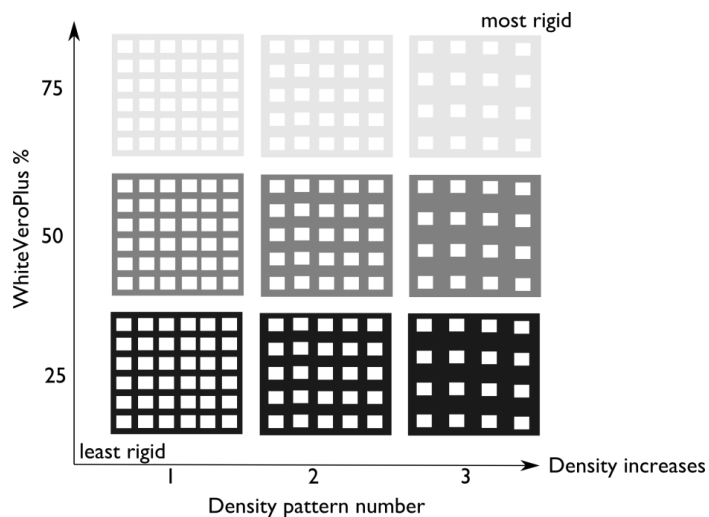
Figure 11-13: Modular weight system using two blended materials and a density component

Weights can be comprised of two components, a value for the proportion of WhiteVeroPlus and a value that signifies one of the density patterns, so:

$$\mathbf{w} = (\mathbf{w_w}, \mathbf{w_d})$$

Where $\mathbf{w_w}$ is a value associated with the amount of WhiteVeroPlus and $\mathbf{w_d}$ is a value associated with a density pattern. For example to model for rigidness, assuming shapes with a lower density of material and a lower proportion of *WhiteVeroPlus* are less rigid, the weight of a new intersection shape in a shape addition could be calculated as follows, by taking the maximum of each of the components:

$$\mathbf{w+u} = (\mathbf{max}(\mathbf{w_w}, \mathbf{u_w}), \mathbf{max}(\mathbf{w_d}, \mathbf{u_d}))$$

Products could be calculated by finding the average between the each value for each component and rounding to the nearest modular step, in this case rounding up to push towards rigidity:

$$\mathbf{w.u} = \left(\left\lceil \frac{(\mathbf{w_w}, \mathbf{u_w})}{2} \right\rceil, \left\lceil \frac{(\mathbf{w_d}, \mathbf{u_d})}{2} \right\rceil \right)$$

Difference could be set as:

$$\mathbf{w\text{-}u} = (\mathbf{max}(\mathbf{w_w} - \mathbf{u_w}, \mathbf{0}), \mathbf{max}(\mathbf{w_d} - \mathbf{u_d}), \mathbf{0}))$$

where 0 would denote a blank space.
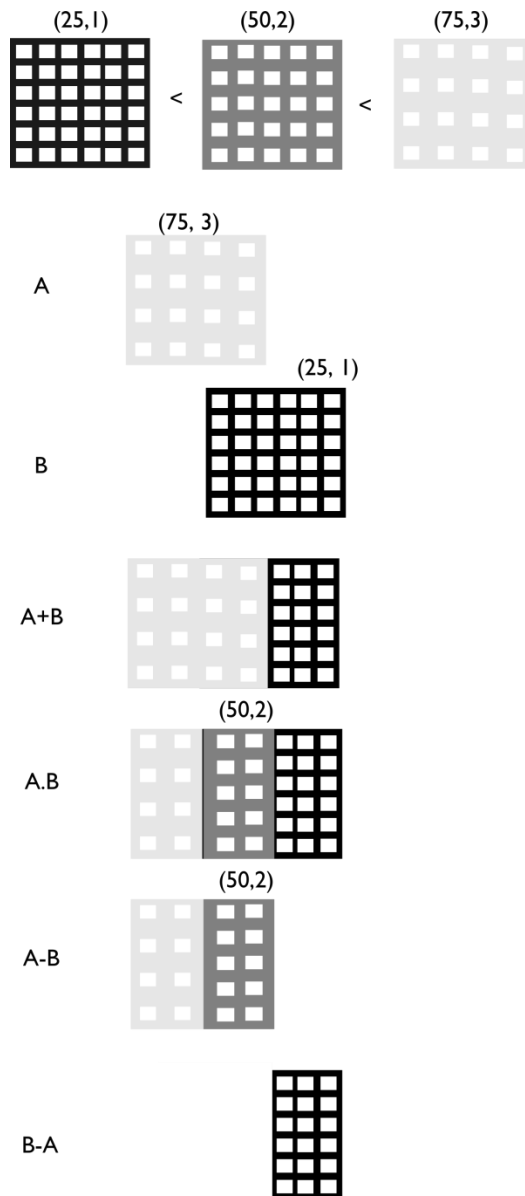
Figure 11-14 Calculating with weights with a density component

Figure 11-14, shows the four example weight calculations with the three density values from Figure 11-13, when shape A and B with weights w=(75,3) and u=(25,1). Intersection shapes are refilled with calculated material and density patterns from the reference scheme.

Densities are created by shapes within shapes, showing that shapes themselves can be represented as weights. How density patterns fill new shapes created by shape operations to provide different behaviours is an interesting and potentially complex design problem for future work.

Similarly to the approach in the colour ink coating example, as shown in section 9.7.2, instructions for weight calculations can be embedded in shape rules to generate designs form Objet Connex 3D printing.

A modular stepping weights tool is applicable for calculating and assigning weights in designs for *WhiteVeroPlus* and *BlackTangoPlus*. A one dimensional scale of materials that can be printed using the two parent materials can be referenced by shape rules to determine changes to weights in design. This could take the form of a wheel or a line configuration of a number of the materials which is then reference by stepping instructions embedded in shape rules.

Ratio scale of % of BlackTangoPlus in material

5%	10%	20%	40%	80%
1	2	3	4	5

Rule with step change of +2

w → max(w+2, 5)
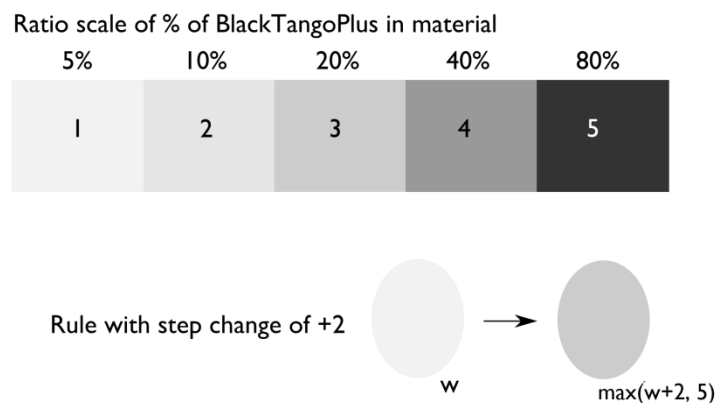
Figure 11-15; Modular stepping ratio scale and rule for Objet Connex

Figure 11-15 shows one example, a ratio scale based on percentages of *BlackTangoPlus* in five materials arranged into a modular stepping scale, a rule underneath shows how instructions can be embedded in rules to instruct new weights on the right hand side of a shape rule application, in this case an oval shape with any of the weights is changed to have the weight two steps above on the scale, the first and last materials act as limits for weights in rule applications.

Another approach is to embed instructions for operations on the weight values in a design in rules without reference spaces to define particular weight relationships. For example
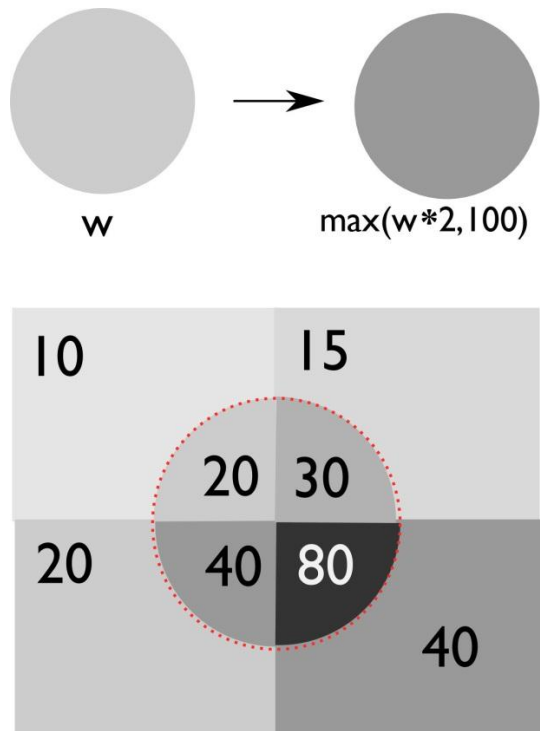
Figure 11-16 shows a rule that adds a circular shape to a design, increasing the percentage proportion of *BlackTangoPlus* in a shape by two times, below the rule an application to a plane comprised of four differently weighted shapes is shown, new weighted shapes are produced in the intersected areas, assigned new weights with twice the percentage of *BlackTangoPlus*.
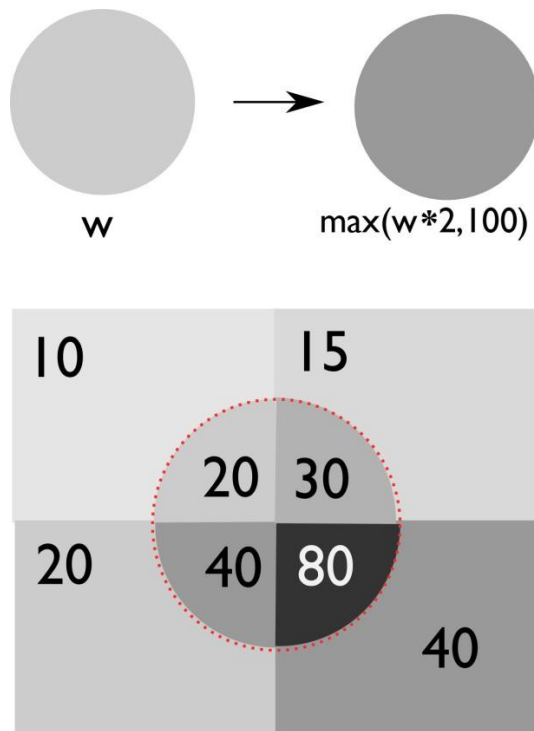
Figure 11-16: Weighted shape rule and application

Despite its simplicity the rule defines a design space of infinite extent, containing shapes with a plethora of different configurations of weighted parts, and consequently, different flexibility behaviours. Changing how material properties are conceptualised can change the design space being explored, potentially suggesting new avenues of discovery.

11.5 Computing with flexible surfaces

Using a computational tool to assign and calculate weights for multi-material 3D printing can also allow the designer to model design behaviours in a computational environment before printing, giving design representations that imitate potential physical objects.

Figure 11-17 shows such a model, a rectangle comprised of differently weighted stripes relating to materials produced by the Objet Connex combing *WhiteVeroPlus* and *BlackTangoPlus*. Next to this is a physical model, created using Kangaroo Physics tools for Grasshopper, where the stripes are modelled as a spring system, with stiffer springs representing the central axes of more rigid areas with greater proportions of *WhiteVeroPlus* and less stiff springs representing areas with more *BlackTangoPlus* and more flexibility, on a

proportional scale. Points can be modelled as an 'anchor' points, initially placed on the *xy* plane. Once running the Kangaroo simulation allows the anchor points to be moved in real time in the Rhino environment, the spring system updates according to these forces, allowing the user to interact and explore simulated kinetic properties of a spring system, and so the potential flexibility of a weighted surface, the user can then 'bake' the spring system at any point, freezing a configuration of lines the shape of the springs. This provides a simulation of the flexible behaviour of the multi-material plane, determined based on the weights applied to the plane in combination with the geometry of the plane. For comparison, the bending behaviour of the physical realisation of the model is illustrated on the right of Figure 11-17. The simulation presents an interactive approach to designing material properties and behaviour: material properties are incorporated in representations used in shape computation, so that they, and the resulting behaviour, can be defined and explored during creative design processes. Figure 11-18 shows the same three design representations of another design, this time with vertical stripes.
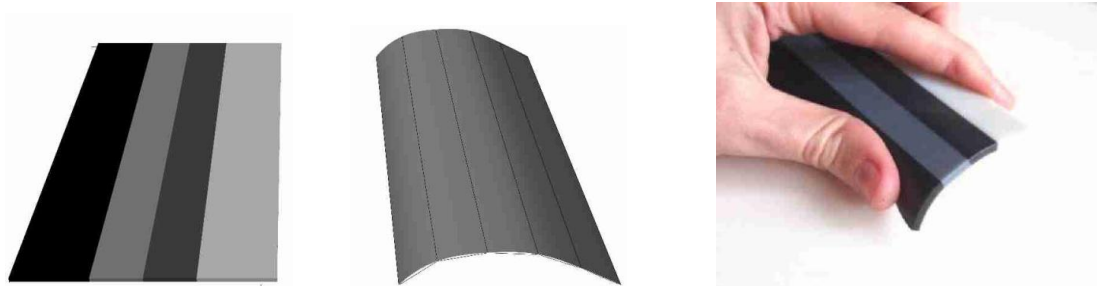
Figure 11-17: Visual representation, computational physical model and printed object
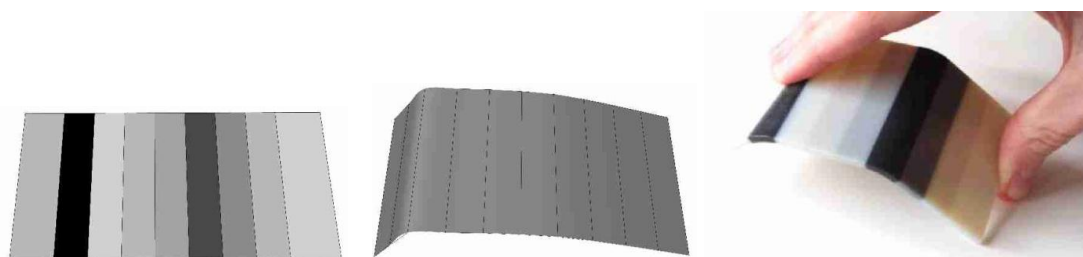
Figure 11-18: Visual representation, computational physical model and printed object 2

Working from these shape computations the flexible behaviours of the resulting surfaces can be simulated. For example, Figure 11-19 presents a simulation of the result of the sum operation, where the two weighted shapes from Figure 11-17 and Figure 11-18 are added, the sum operation assigns the greater of the two weights to each intersection, in this case darker, more flexible materials are deemed to be greater than lighter more rigid materials. The resulting shape can again be modelled by a grid of springs, assigning a proportionally flexible spring to each shape, which can then be manipulated in real time in the Rhino environment using Kangaroo simulation and the anchor points. Figure 11-19 shows one possible configuration created by such a manipulation, a doubly curved shape, combining the orthogonal curving of the two original surfaces in an interesting way.
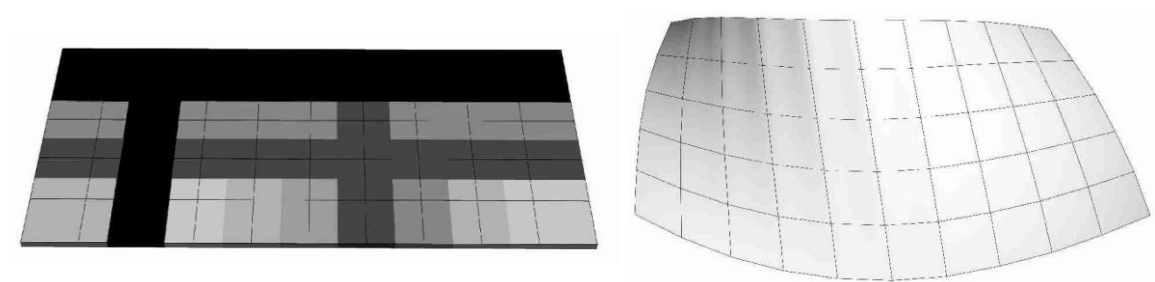
Figure 11-19: Weighted surface, result of the sum operation, visual and physical models

Computationally modelling the physical behaviours of weights in this way gives the computational maker an additional tool to explore possible designs, getting a feel for possible behaviours before physical objects are printed. Kangaroo also offers tools to model the application of forces on the end points of springs, a broad range of different force tools are available, from single vector forces, point attraction and repulsion forces, bending an shear forces to mention a few. It also offers tools to create forces that will pull the points of a spring system to a static surface. This in particular could be useful for exploring moulded and or reconfigurable designs for multi-material 3D printing. Applications for this could be textiles that fit round a part of a body, the shape of which has been modelled or even scanned into the CAD environment, or for larger scale architectural fittings that fit certain places, or reconfigure and adapt to change the boundaries of a space.

Three possible approaches to using shape grammar weights to generate objects for printing with the Objet Connex, related to two of the available materials, *WhiteVeroPlus* and *BlackTangoPlus*, have been presented in the previous sections. These approaches are tools that can be used or transformed to generate new objects. A design brief was co-evolved with the weight tools with the aim of making a patterned textile for printing on the Objet Connex, which would provide flexibility in a specified way. This design experiment was used to explore and prove the role of weights to support creative computational making design processes.

To begin a rectangular surface was set up and divided into a square sectioned grid, these were then modelled as springs using the Kangaroo Physics tools for Grasshopper, in the Rhino environment. The four corners of the grid were assigned as anchor points, the simulation was started and the grid manipulated by the author in real time by dragging the anchor points around with the mouse. At a point chosen by the designer the simulation was then stopped and 'baked', giving a new, doubly curved, configuration of the grid. This approach allows the designer to explore shapes that a flat but flexible printed object could potentially be manipulated in to, if the springs are modelled with an approximate feel of the Objet Connex materials. In this case all the springs were given an equal, moderate stiffness, to allow equal bending at any point. There is no reason that each spring could be given a different stiffness if the designer has a pre designed or generated weighted shape.

Once a configuration of the grid modelled as springs has been selected weights can then be applied to the original flat rectangle. The weights are parameterised by finding the curvature value at the spring junctions in the 'baked' spring system's matching surface using the Grasshopper curvature analysis tool. Figure 11-20 shows a reconfigured surface and the corresponding weighted shape below. On the flat shape a cylinder is placed at each point and given a weight according to the curvature on the configured shape, areas where the curvature is at a maximum are assigned black cylinder comprised of entirely *BlackTangoPlus* to allow maximum flexibility in the final printed object. Areas with zero curvature are assigned white

cylinders, to be printed entirely in the rigid *WhiteVeroPlus* material. The curvature values are remapped onto a scale of ten steps between 100% BlackTangoPlus and 100% WhiteVeroPlus, providing a proportional value of the two materials, represented in a scale of colours from white, through greys to black.
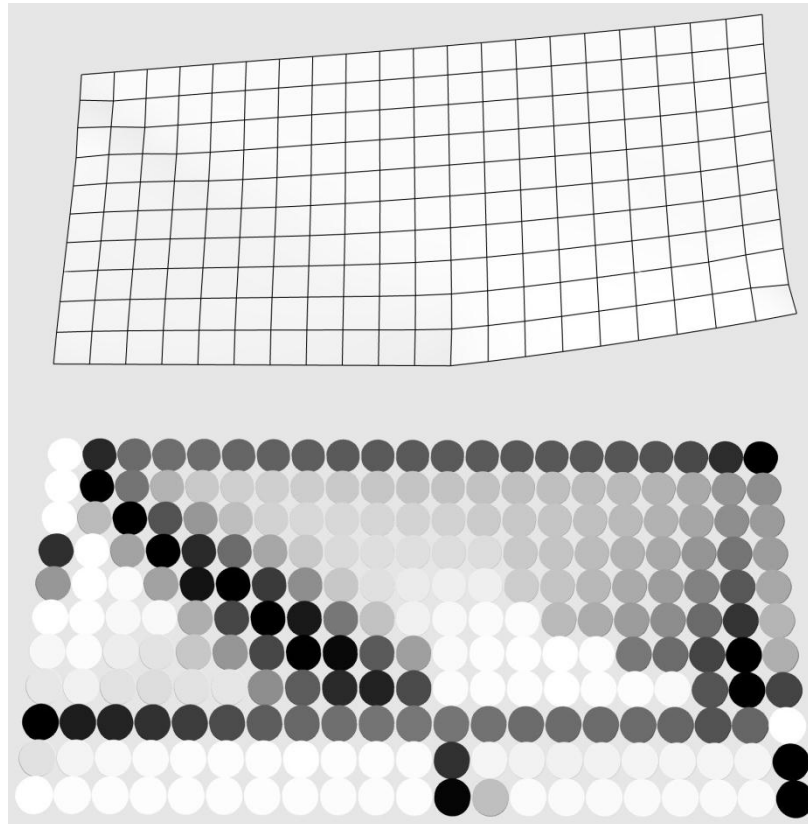
Figure 11-20: Reconfigured Shape with corresponding flat weighted shape

As can be seen areas on the rectangle that had undergone more bending in the simulation were assigned darker materials with a great proportion on *BlackTangoPlus*, in order for the flat printed object to bending capability in these areas.

Using a system based on shape grammar weights to design reconfigurable textiles gives the designer the opportunity to explore shapes in the design while still managing multi-materials and the associated properties. For instance increasing the size of the cylinders produces an overlap, between each one and its surrounding shapes, which also joins each cylinder so the shapes become a single piece of printed textile. The material in this overlap can be calculated

be using a weights system. For instance Figure 11-21 shows the same shape modelled in Figure 11-20, except this time larger diameter cylinders have been placed, but also the overlaps have been resolved as individual shapes using the Boolean intersection tool in Grasshopper. Referring to the weights tools developed in section 11.1 the designer selected a way of calculating the weights of these shapes that seemed pertinent, a product calculation that returns an averaged rounded value of the two parent cylinder weights to one of the modular material steps. This gives a transition between each cylinder in an attempt to create a smoother flexibility of the printed textile.
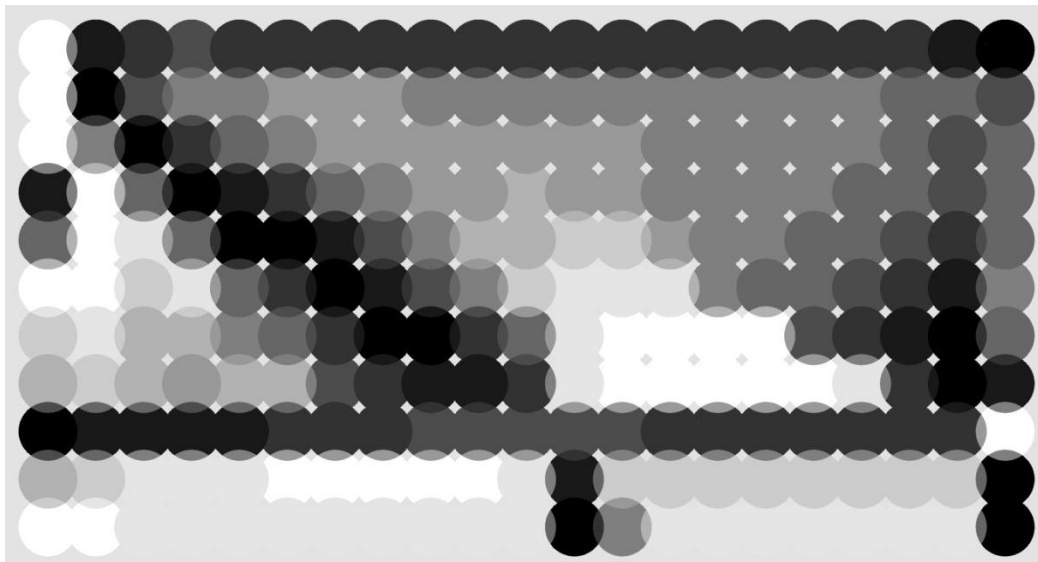
Figure 11-21: Visualisation of multi-material printed textile using a weight product calculation

This resulting weighted, printable shape could be subjected to further useful weighted shape transformations. The designer could perform additions with other weighted shapes to try and combine further behaviours into the design, as could be seen by adding the vertically and horizontal weighted shapes in section 11.5 or by using focussed instructive rules to add extra flexibility or rigidity in the design as was described in section 11.3. Shape differences could provide features such as holes in the textiles where the designer may want to allow air or light to travel through the textile, reduce the density of both or one of the combined materials. Difference could also be used to decrease or increase flexibility or rigidity in an area by performing weight subtractions. The designer can take the weight tools defined in this thesis

and use them according to their design requirements to generate new and potentially creative outcomes.

11.7 Discussion of weighted shapes for multi-material 3D printing

Addition, product and difference transformations and accompanying weight calculations may have unexpected results on the behaviour of an object, the relationships may not be continuous in ways that the maker expects. It is likely the designer would undertake a symbiotic process between the computational modelling of a weighted surface and the actual printed objects to find relationships between shape operations and weights and physical behaviours in the printed objects which could then yield useful and creative designs. This kind of process is very reminiscent of the findings from the first part of this thesis. Tools and rules are put in place to generate outcomes, which then can be used to reconstruct and alter sets of rules and tools as a method of stimulating creative episodes.

Neri Oxman [81] has also investigated multi-material 3D printing in her research. Her approach theoretical approach is that of bio-mimicry, where objects are computationally 'grown', areas of material are influenced by the environment to form in a certain way. In one paper [81] the approach was to model a multi-material printed object in a similar way to the first step on this design experiment, a surface was divided into a large number of small squares, each assigned a varying material between *BlackTangoPlus* and *WhiteVeroPlus* according to the force a corresponding spring was subject to. The overall visual appearance is a more organic patterning, which is ultimately made up of small squares, but appears more analogue than digital to the eye.

Using weighted shapes in such computationally generated designs offers the designer-maker more opportunities to explore unlimited kinds of shapes and patterns while still being able to manage multiple materials and properties in one printed design. The designer could easily explore beyond the obvious two dimensional tiling systems such as square, triangle and

hexagons by using any shape, weighting it accordingly and then using addition, product and difference calculations to further transform the visual appearance of an object, producing more complex geometric patterns, yet retain control of the material properties of the object. An infinite of number of shapes could be used, with no need to have repetition if it was not desired. Unlike the Neri Oxman [81] example, weighted shape rules offer and may even encourage the computational designer-maker to perform further transformations on designs, with further shape rule applications.

Due to the nature of 3D printing, where objects are printed in layers of material in the z axis, flatter objects are more economical to print due to a reduced amount of printing time. Printing a three dimensional object in a flat configuration brings economic benefits. This example produced a 2.5D textile that can then be reconfigured according the areas that have been printed in the more flexible materials, however more complex three dimensional weighted shape configurations could be modelled and manipulated and printed.

Carrying out the design experiments detailed in the previous sections has allowed the development of a framework of conventions that need to be addressed when constructing a weights system for computational making using multi-property and multi-material 3D printing systems. These can be arranged into a schema, a general set of related components for a designer to use as a guide to planning and using them.

Not every item in the schema needs to be defined, some can be conscientiously omitted or will not necessary in certain scenarios, for instance the designer may only be concerned with weight results in intersections resulting from shape additions, so may not wish to define the product and difference calculations. This schema offers computational designer-makers a general tool to guide them in the process of using weights based system to handle some properties in a computational design tool.

Figure 12-1shows the weights schema, designed as a chart to show the decision making process involved. Three black outlined boxes show the three main areas that need to be considered when arranging a weights system; selection of weights that will be used and the relationships between them, the selection of a method of calculating weights as they interact and supplementary considerations for the designer that may or may not be necessary. The decisions the designer makes as they step through the schema will be informed by the goals of the computational making process and the properties of the multi-material 3D printing system that will be used to make the object.

Weight schema for multi material/property 3D printing
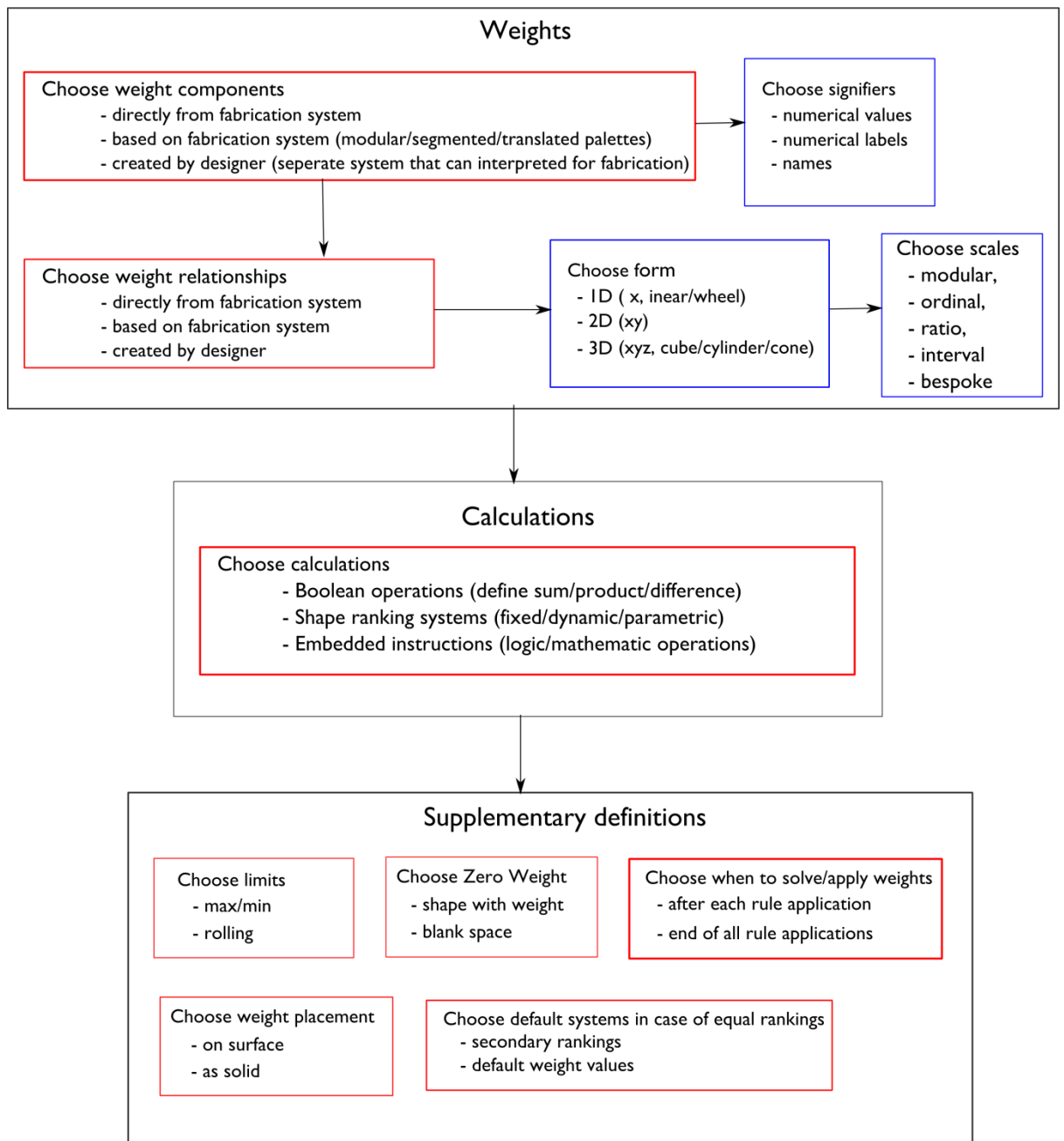
Figure 12-1: A weights schema for multi-material/property 3D printing

To give more detail each box in the schema is explained below.

Weights: Designers must first choose a range of weights they wish to use that are appropriate to the design and making goals, these could be all or selected materials produced by the fabrication technology being used, or could be a contrived range that are interpreted into something the technology produce. These can be denoted by numerical values or labels.

These weights can then be organised into a geometric structure to help inform and be used as a reference for the calculations for weight interactions.

Calculations: Some kind of calculation is performed using the weights to produce the weight of new shapes in a design produced by transformations. Three distinct way of calculations were found in this research; Boolean operations, where calculations for sum, product and difference are defined and used; shape ranking systems, where fixed or dynamic values or labels associated with shapes are referenced in calculations; and embedded instructions, where each rule carries out specific operations on weights.

Supplementary: This component of the schema encapsulates the supplementary decisions that may or may not have to be defined in a weights system for multi-material 3D printing.

- **Limits –** Maximum and minimum limits of weight values may be required. Alternatively the designer could have a system that warrants a wrap-around if the weights can be arranged in a circular relationship, such as a colour wheel.

- **Zero Weights –** As was discussed in section 10.14 a zero weight can mean a blank space or a shape with a weight with a numerical value of 0, the designer can choose.

- **When to apply/solve weights -** This represents the decision whether to embed weight interactions in each rule application or at the end of a generation process, as discussed in section 10.13.

- **Weight Placement –** 3D shapes can be viewed as solid shapes or a collection of surfaces and this can affect the way weights are calculated, as discussed in section 10.12

- **Equal Rankings -** Some shape ranking systems may deliver equal rankings, so a secondary calculation or default may need to be defined, as discussed in section 9.4.

This schema has been developed by a research through design process, centred on two types of systems and an examination of the properties of colour and flexibility and weights theory. Weights could be used to computationally model many other material properties, so it is likely that this schema is not exhaustive of all the considerations for every weights system. The schema stands as a work in progress, hopefully to be developed further as more computational design experiments with using weights are carried out and new factors in their use are uncovered by further research, but stands as an initial resource for those interested in the possibilities.

13 Conclusions

This chapter reviews the theoretical, methodological and technical contributions made by this thesis and examines the implications of these in the context of shape grammar, designer-maker practice and computational making. This research was driven by a wish to discover useful knowledge about design through making in order to aid designer-makers working with physical tools and also those working with new computational and digital fabrication tools.

The contributions here are in fact tools for designers; theoretical descriptions and strategies for guiding design-through-making processes towards creative episodes and a schema for computational making practice using shape grammar weights to generate multi-material design representations for 3D printing. Like the findings, all these tools are open for experimentation and transformation, hopefully offering opportunities for new tools and new outcomes.

This chapter begins by revisiting the research questions and answering these on the basis of the results of carrying out the research. This is followed by a discussion of the context of these findings, how they compare and contrast with the work of others in the associated research fields of shape grammar, design, craft and creativity. The contribution to knowledge section gives a clear overview of the new knowledge produced by the research for the reader. This research and the findings have opened up areas that can provide further lines of inquiry and these are detailed in the future work section. Finally the author has provided a personal reflection on the research and how it has aided and informed her own designer-maker practice.

13.1 Revisiting the research questions

This section revisits the research questions of this thesis and summaries the findings in relation to these. The main question posed at the start of this research was:

How can shape grammar support creative making?

This research did demonstrate that shape grammar can be a useful tool for both describing and doing making that generated creative outcomes. The thesis is segmented into two parts as this question can be interrogated from two approaches, as shape grammar can be used in two ways in design, in both design theory and practice. The first part of this thesis considers shape grammar as a method of describing and modelling tool activities in design-through-making processes. It was found that Stiny's design rule schemas could be used to categorise these tool activities, often the site of creative episodes. The result is a set of clear strategies that designer-makers could use to help elicit creative outcomes in their design processes, thus schemas from shape grammar can support creative making. The second part of the thesis examines the use of shape grammar way of designing, by using rules to transform shapes and generate new designs. To do this the feasibility of using shape grammar weights in computational making design processes, to generate objects for multi-material 3D printing, was tested with design experiments, finding that weights did offer tools that were of use and could be transformed to produce creative outcomes.

The answers to the following sub questions reveal how and why shape grammar was found to be a useful way of supporting creative making in these contexts in more detail.

How do creative episodes occur in designer-maker practice?

The interviews with designer-makers, recorded general discussions on recent design processes they had undertaken, and other secondary sources, were reflectively analysed with attention to the accounts of creative episodes. It was found that these episodes and more general parts of the conversations were dominated by descriptions of the selection, use and transformation of tools.

It was found that the main activities involving tools that designer-makers partook in could be categorised into the activities of tool addition, tool combination and tool transformation, and each as found to have the potential to yield creative episodes when certain tactics and mechanisms were used in these phases. Purposeful attempts by the designer-makers were

observed in the evidence to find new uses and new combinations for their tools, and they sought to transform and build new tools for their personal design. The creative mechanisms that aided these activities were found to concur with established creativity research; the designer-makers were found to use analogies, concept blending and emergent features of tools as the key to creative episodes in the these tool activities.

Can shape grammar be used to describe designer-maker activities?

To allow the application of shape grammar theory to designer-maker practice an analogy between rules and tools was made, rules transform shapes and tools transform materials, allowing a bridge between the two design spheres.

Stiny's [109] design rule schemas use a notation based on shape grammar rules to describe activities in design that go beyond shapes and onto any materials used in a design process, such as concepts or previous designs. By considering each of the schemas in the context of tools and materials reciprocal activities could be exemplified in making processes, each is detailed in section 7.1. Shape transformations such as boundary isolation and addition or can be modelled as making processes where materials are chosen, combined and shaped. However referring to the findings on designer-makers' creative episodes involving tools it was found that these operations were not just performed on materials but also on the tools themselves. The rule schemas provide classifications of transformations that can be applied to tools by designer-makers with potential to produce creative episodes. This provides designer-makers with a range of strategies that they can consider for the way they use tools in the hope that may stimulate creative outcomes.

What can shape grammar theory gain from designer-maker practices?

Analysing making processes through the lens of shape grammar revealed some procedures and cases in making that are not represented in shape grammar theory, these findings could be incorporated into shape grammar theory, extending the possibilities of the theory.

It was shown that designer-makers were subjecting not just materials, but also tools to the operations in Stiny's shape grammar schemas. Tools may be a special kind of rule, one that has some description or material presence, be it physical or digital, that permits transformations to be made on it. The author demonstrated some extensions to Stiny's [109] shape grammar schema notation where transformational rules are subjected the schemas, these can then generate new shapes or designs.

Strategically transforming tools rather than designs was an important activity for the designer-makers, co-evolving tools and the generated objects until a useful tool and design outcome were generated. Again, interpreting this into shape grammar equates to performing transformations on rules, Knight [55] suggested that rules could be modified to create new design languages, this research concurs with that and further to this proposes that rules themselves can be subjected to Stiny's rule schemas to transform them to produce novel rules and outcomes.

Stiny's [107] emphasis on the application of shape grammars in design was the idea that they could be used in an improvisational manner to transform and evolve a shape or a design, consistent with Schön & Wiggins' [94] see-move-see designer protocols. The findings of this research suggest a different tactic by designer-makers, where the focus of improvisational transformation is on the rules and set of rules (in these cases tools) observations made from the generated objects then inform the next tool transformation and so on, a case of *see - transform tool - see*.

Are shape grammar weights a useful way to generate designs for multi-property 3D printing?

The second part of the thesis used a number of computational making experiments to ascertain the viability of using shape grammar weights as a generative design tool to generate objects for two multi-material 3D printing systems. As these experiments unfolded it became clear that shape grammar weights are a tool in themselves; a set of operations with associated

conventions and calculations that can be calibrated, transformed and interpreted into computational tools for the generation of digital representations and indeed produced designs suitable for printing. Weights solve a particular problem in designing for multi-material printing in the Rhino environment, and perhaps other CAD packages where distinct shapes can occupy the same space, by providing a way to calculate and assign suitable material properties to intersections of shape intersections.

Can using shape grammar weights provide opportunities for creative episodes?

Logical reasoning and applied design experiments with weights allowed the author to build a method of defining weight systems appropriate for some different computational making situations, this was presented as a general schema in section 12. Weights can provide a system to manage and explore material properties in computational making, yet by applying weights theory to different 3D printing systems it became apparent that weight tools need to be formulated to suit the properties of the system and the aims of the designer. The strength of shape grammar weights is its capability to allow adaptations for different material systems, designer aims and potential creative transformations within the fundamental principles.

The weights tools developed for the two 3D printing systems propagated two further design experiments that made use of the material properties of the systems and shape intersections. Both experiments produced new designs for multi-material 3D printing, and featured creative episodes achieved by transforming and using the weights tools that were previously defined and built.

What can shape grammar weights theory gain from this application?

The focus on weights in Part 2 of this thesis also found some parts of the theory that could be defined more formally and extended. Working logically through weights examples using colour with Knight's [59] colour grammars and Stiny's weights system as a basis gave rise to some new definitions when they were applied in real design scenarios.

The design experiments demanded a formulaic approach to setting out operations, calculations and conventions for the properties of each material system. This lead to specific computational tools and models for the 3D printing system used in the experiments, offering applied designerly knowledge and tools relating to shape grammar weights theory. This was distilled into a more theoretical schema to guide the use of shape grammar weights in computational tools for generating multi-material objects, offering more detail on many aspects of the use of shape grammar weights than has previously been clarified by others.

13.2 Discussion

Through the author's designer-maker practice experience and the chosen research topic two spheres of design were brought together, that of design-through-making and shape grammar. At first glance these two spheres seemed disparate; from the author's experience of talking to many other designer-makers no one had heard of or used shape grammar in theory or practice. Previously shape grammar research had been focussed on paper based, computational or theoretical applications, not making, although the shape grammar research community has started consider this subject recently [62,64]. Equating the processes of transforming shapes with rules and transforming material with tools to generate designs provided the link to explore how shape grammars could support creative making; *the tools are the rules, the rules are the tools*. Creativity was specifically chosen as a focus as it was assumed by the author that creative episodes were a signifier of successful making processes, where outcomes were new and useful and could therefore we used as a way of validating any findings as useful knowledge to designer-makers and others.

Shape grammar can be used in two ways, one is as a theoretical way of modelling designer processes, with the intention of helping designers and researchers understand actions performed in a design process and the reasons why, hopefully improving design practices. To follow this line of inquiry the approach of *research about design* was selected, and the method of gathering evidence from interviews, observations from design processes by the author and

research by others was chosen. This was then analysed by comparing descriptions of creative episodes with established theoretical ideas from creativity, design and shape grammar literature.

Since the research was begun some of the main shape grammar proponents have also made links between shape grammar and making, Knight and Stiny [65] published a paper in 2015 titled *Making Grammars*, demonstrating how vernacular, rule based making processes, like decorative knotting, can be modelled with visual rules. So far they have not addressed what Pye pointed out many years ago – that making is for the most part mediated by tools, very few making processes are done solely by hand. This research has taken a detailed look at how professional designer-makers go about generating designs, with the aim of finding a deeper understanding of how creative, successful design-through making processes are achieved and using shape grammar to model these. Designer-makers selected and used tools in different combinations, much like rules in shape grammar, to generate designs by transforming materials. This research uncovered activities that goes beyond this, that of adding, combining and transforming tools, activities that could yield creative episodes if a approached in a considered way. Stiny's [109] design rule schemas provided a useful way of classifying the kinds of transformations designer-makers were seen to apply to their tools. The designer-makers' focus and design reasoning lay on the activity of transforming the rules/tools in an exploratory and improvisational way, an activity proposed before in shape grammar research as a way to produce new designs [55, 56, 57, 58] or redesigns [3, 17, 18, 54].

The findings from this research process produced new knowledge about designer-maker practice and offer some formal descriptions and classifications of some of the activities that this kind of designer may use to design and make. In surveying design research, a summary of which can be found in the literature review, section 2.2, the author found that designer-makers, designers who design by directing manipulating tools and materials and produce the finished objects had not been studied specifically; design research has been primarily concerned with architects, product designers and engineering design and on verbal,

representative and intellectual design reasoning. For the first time this thesis has examined the practices of designer makers in an analytical way, and craft processes addressed rationally, rather than in a historical, critical or aesthetic way.

By characterising design-through making and craft as a series of transformations, similar to those found in shape grammar, on materials with tools and on the tools themselves, for the first time some rational descriptions of craft practices have been set out. The framework of tool related strategies and the weights schema produced by this research encapsulate designerly knowledge, or perhaps 'makerly' knowledge, that can be used to guide and inform designers wishing to explore design-through-making. Both these outcomes contribute to the fields of craft, design and their relationship by offering both an approach to model practices and some new insights into what some of the practices are.

Technological advances has always provided new tools at the designer's disposal, and most recently the digital revolution has provided a plethora of software and hardware for designing and making objects, therefore understanding the way designers can use tools creatively is likely to continue to be important. New digital fabrication techniques and generative design tools have created a renewed interest in how craft, tools and materials are used, McCullough [77] and Rivka Oxman [85] have pointed out the similarities in the use of digital and analogue tools, so it would seem studying designer-makers who have mastered the creative manipulation of tools is a valuable endeavour and may have relevance beyond the sphere of craft and making and be useful going forward into the digital future we face. Fischer [37] conducted a digital tool making study, giving generative design tools to architecture students, but found that they struggled to produce designs with any novelty, he came to the conclusion that the his tools were too prescriptive, not leaving room for any new '*un -encoded*' discoveries that would be desirable in design. He suggested that digital tools either have to support a rich variety of actions, like their analogue counterparts, or that the designer must be involved in the actual tool making process for any hope of a novel outcome.

This study has found that designer-makers mitigate this very problem in several ways; by manipulating and building tools to produce custom tool processes that can generate new outcomes. The transformational operations on tools in designer-maker practice ranged from changing the contexts and combinations of tools, to more fundamental parametric, functional and reformatting modifications. The key was that a representation, whether physical, digital or conceptual of a tool was open enough to the designer-maker for them to be able to alter it in some way. In the second part of this research, which was a digital tool building exercise these same kind of transformational operations were seen again as the author built and revised computational shape grammar weights tools to work with different weight definitions and printing systems, culminating in new designs for the printing systems with novel attributes. These findings are echoed from a completely different viewpoint and time by craftsman and designer David Pye [89] who suggested that closer control of analogue tools led to greater 'diversity' something he perceived as an aesthetic concern, but can allow re-interpretation to creative outcomes, and Dormer's [28] concerns about the ubiquitous output of the first software design tools.

Designer-makers often used tools as the prime focus for constructing and exploring design worlds, however one of the interviewees did provide an exception to this way of working, a designer working with digital tools in the realm of corporate advertising. Her descriptions of design processes revealed her tools, software packages, were a means to an end, not defining features of her design world or a significant source of creative episodes. There are many differences between this kind of design process and that of the designer-maker that are likely to contribute to the different activities that occur. The main difference was that this designer was under pressure to deliver fairly specific design solutions in limited timeframes to satisfy colleagues and clients, leaving little scope to experiment or co-evolve tools. The strategies discovered in this research may not be useful in some design processes, and the research did seek to focus on a particular kind of designer for the most part. If a designer from a different

discipline had the time and inclination to seek new creative opportunities adopting the tactic of tool transformation could be relevant, but may not always be suitable or easily undertaken.

The second part of this thesis sought to examine how shape grammar could support creative making in its other form; as an applied design method, using computational rules to generate designs from shapes. A specific task was chosen that hasn't been attempt before, using shape grammar weights to generate objects for multi-material 3D printing systems. Shape grammar weights are a way of representing and calculating with shapes with different properties that can interact with one another, so potentially appeared to be a good way of designing for these new printing technologies. This line of inquiry warranted a *research through design* approach, with the method of performing computational design experiments using shape grammar weights to discover their viability as a computational making method. The result was a range of computational tools, built in Grasshopper for the Rhino CAD environment that generate objects for multi-material 3D printing, each version is transformed to handle the two systems used as case studies.

The process of building and exploring computational weights tools echoed much of the findings from part one of the thesis, the author constructed new tools that were subjected to various transformations and produced creative insights. The capacity for the production of novel artefacts was demonstrated although the full extent of how the weights tools could be used for creative ends is yet to be explored.

These Grasshopper tools could be appropriated by other computational designer-makers with an understanding of the software platforms, however the knowledge gained from the building of these tools was distilled into a weight schema. This weights schema is a conceptual tool, transferable and transformable for those interested in this way of generating designs with multiple materials with variable properties. This schema is a dual contribution to computational making, a tool to create weights systems that can manage the problem of

assigning properties to shape intersections, and shape grammar weights theory, by defining and formalising in a clearer way the choices and decisions that define weights systems.

Previous weights definitions by Stiny and Knight [108,106,59,61] have not addressed some of the circumstances that the design experiments exposed, such as weights comprised of two or more components that can be independent or related, possible ranking systems and embedded instructions, and how weight application and zero weights can be handled. It was found that a universal weights definition is not going to be applicable in computational making for every possible material property, weights theory has to act as a tool; a tool that is open to transformations and reinterpretation.

13.3 Contributions to knowledge

As was seen in the literature there is a gap in design theory research concerning investigations into the work of designer-makers, despite craft playing an important role in design. Contributions to knowledge to the three spheres brought together in this research are now clarified.

For the first time design-through-making has been characterised as a series of rule based transformations on both materials and tools, similar to those found in shape grammar, offering new descriptions of some of the tool activities and also an approach to model them, this contributes new ideas to the field of craft and design theory, where no previous attempts to model designer-maker practices have been made.

Designerly, or perhaps 'makerly', knowledge has been found and presented in the form of new strategies and schemas that designers can use to support future design processes, contributing to the fields of design theory, craft and digital design. This knowledge hopefully supports designers who wish to undertake creative design-through-making processes by informing them of significant activities. The specific findings that make up this body of knowledge now follow.

Tools are used in the definition of shared and personal design worlds. Previous, established design theory has shown that designers build design worlds with design materials [93], grouping concepts, previous designs, models, prototypes and conventions which they will manipulate to generate design solutions. For the first time designer-maker design worlds have been investigated and tools were found to be one of the primary ways they defined shared and personal design worlds.

Three specific design activities involving tools were found to be the basis of creative episodes for designer-makers: Tool selection, tool combination and tool transformation. The selection and application of tools to build design worlds was at the forefront of designer-maker practice, the way and order tools were used was considered carefully, novel approaches to these activities, by using unusual tools in unusual ways or combinations, was seen to be the seed of creative episodes. These are concepts new to design theory but supported by Boden's [10] descriptions of creativity, where creative ideas stem from the exploration and transformation of sets of conceptual rules, but this research has revealed that designer-makers perform these activities on physical entities; tools.

Two kinds of tool transformations were found in designer-maker practice: parametric tool transformations or functional tool transformations. Designer-maker tool use has not been studied specifically in previous design theory, this research found examples of tool transformation that could be categorised into these two activities, where designers altered extrinsic parametric variables present in the tool, or more intrinsic functional aspects of the tool, in turn these transformations allowed tools to generate new, creative outcomes.

Designer-makers used established creative mechanisms, but often performed these using tools and tool concepts. Creative episodes that occurred during the activities of tool addition, tool combination and tool transformation were aided by creative mechanisms. The creative mechanisms used matched those from established creativity research, using analogies, concept

blending and harnessing of emergent features were seen to catalyse creative episodes with tools, but also used tools as a basis for the mechanisms.

This research discovered that Stiny's design rule schemas are a useful device for describing designer-maker tool activities and can provide strategies to support creative making. Transforming shapes with rules can be aligned with transforming materials with tools, in turn shape grammar schemas aligned well with making processes. Stiny's schemas and notation were used as a basis for classifying the tool activities, new schemas were developed to demonstrate how tools, and therefore rules, were subject to the rule schemas, extending the classifications of possible ways to transform rules in shape grammar. The schemas offer designer-makers clearer strategies for increasing the likelihood of creative episodes through considered tool activities.

The detailed analysis of the author computational making process also revealed an approach to designing and making an object previously undocumented in design research. Dorst and Cross [29] found that designers co-evolve the problem and solution spaces and then use new information to make a creative leap between them, to then satisfying the problem. This research found a similar but new perspective on this in designer-maker processes, that of co-evolving tools and outcomes. Also Stiny [108] and Schön and Wiggins [94] suggest a designer's focus is on a design representation which they appraise, transform, observe the results and repeat this until a solution is found. This research found that designer-makers have a different focus, cyclically transforming the tools/rules and observing the outcomes until they have a tool or tool combination to produce a solution.

The second part of this thesis examined how shape grammar, in particular shape grammar weights, could support creative computational making for multi-material 3D printing. The contributions to knowledge gained by the design experiments and accompanying reasoning are now summarised.

The design experiments produced a set of weights tools for use in computational making processes using multi-material 3D printing for calculating the weight of shape intersections. The tools take the form of Grasshopper tools for Rhino, however they are more likely to be useable in their abstract form, sets of operations (sum, products and difference) with associated calculations that can be used as is or transformed and then interpreted into tools for the designer-makers chosen digital medium. Specifically these take the form of new colour weight tools for the RGB, HSL and CYMK colour spaces. Each colour space required a specific approach according to the characteristics of the system, including for the first time addressing how to calculate with weights systems that have two and three components. Secondly weight tools for the Object Connex printing system were presented, for the materials WhiteVeroPlus and BlackTangoPlus, to manage material properties in shape intersections. These new weights systems not only take into account the interdependence of the proportion of the two materials but for the first time take into account the relationship between design objectives and material behaviours of the design problem in a weights system for material properties.

These tools also contribute a new more detailed general weights schema for developing tools based on shape grammar weights for other computational making applications, by laying out a framework of operations and conventions to fulfil to create a tool to manage material properties in shape intersections. This takes the form of defining calculations for the sum, product and difference between weights and also defining values for the limits and modular weights steps, and also making a decision on how to handle zero weights.

An initial review of Knight and Stinys' various systems led to some extensions of general shape grammar weight theory, reasoning for computational making allowed some theoretical level observations that can be added to shape grammar weight theory. In the first appearance of material properties being incorporated into shape calculations, Knight [59] suggests that opaque colour fields added to a design dominate fields already present in chronological order, as a designer or artist would perhaps collage pieces of opaque paper. This notion has been formalised and made more flexible by the definition of shape ranking systems. A shape ranking

system can be based on chronology, as suggested by Knight, however new ways of ordering shapes were deduced by this thesis, they can be assigned or parametrically related to shape attributes, and can be fixed or dynamic throughout a design process.

Another new extension to existing shape grammar weight theory is the approach of embedding weight calculation instructions in shape rules. This was initiated by Knight [61], suggesting shape rules containing weight representations could be used to transform weights by stepping them along a modular scale with successive rule applications, however this thesis has formalised and extended this into an approach of including calculation instructions in shape rules to produce new weighted shapes after a rule application, these can use any mathematical operators to manipulate values associated with the weights.

Building tools for standard colour spaces also the status of these systems as tools, tools that could be transformed or invented themselves. This thesis showed that bespoke colour palettes, a group of colours arranged in 2D or 3D space can be used as a reference tool for weight calculations. Colours can be related in some kind of attributed scale or could be chosen from other sources such as branding or coding systems and arranged in any way the designer sees fit.

Finally the design experiments showed that shape grammar weights can support creative computation making by providing a flexible tool framework for managing and exploring material properties in designs for multi-material 3D printing.

13.4 Summery and conclusions

This thesis set out to discover how shape grammar could support creative making, a relevant concern as many designers continue to turn to making processes of all kinds to inspire, inform and make their prototypes and finished objects and little attention has been given to this in design research. Aligning rules with tools provided a link between to analyse the link between shape grammar and design through making. In many ways designer-makers work like other

designers, using design worlds and known mechanisms for creativity, but this thesis learned that this is often done through tools and tool concepts, and design solutions are generated with personalised tools. Specific kinds of significant designer-maker tool activities have been observed and classified by this research, tool selection, combination and transformation, often found to be the site of creative episodes. Designer-makers used operations on tools, in common with shape grammar schemas, operations such as addition, selection, subtraction and parametric transformations were all exemplified by the thesis. Using the design rule schemas to model designer-maker tool activities also brought new propositions to shape grammar theory, concerning potential to transform transformational rules, and a that this is where a designers primary focus may lie, rather than on the shape itself, as was observed in an analysis of a computational making process.

Shape grammar weights were also examined as an applied design method for generating designs for multi-material, multi-property 3D printing by working through and documenting pragmatic design scenarios. The outcomes, a range of computational tools tailored to various systems then distilled into a general weights schema, revealed that weights systems can be characterised as tools; tools that are defined yet malleable enough to allow the same kinds of tool transformations observed in the first part of the thesis. A final computational making process was undertaken, where shape grammar weights supported the realisation of a design-through-making process via tool transformation, resulting in creative episodes and outcomes.

13.5 Future work

The findings of this thesis have opened up further avenues for inquiry both on the subjects of design-through making and shape grammar.

This thesis gathered evidence on designer-maker tool use from interviews, observations from the author's personal design processes and other sources. This initial evidence was not done with any presumptions about a narrative for the thesis, the focus on tools and tool activities

emerged as the analysis in conjunction with related literature was developed. It is possible that further interviews or observations, informed by the findings from this research, may be able to find further examples and definitions of tool activities and or attempt to address other aspects of designer-maker practice such as interactions with materials, learning and expertise. As has been mentioned designer-makers have been neglected in design academia, therefore further research into any part of these particular kinds of designer's practices is ground that could and perhaps should be surveyed in the future.

This thesis has established that shape grammar schemas can be a useful ways of describing designer-maker actions, both on materials and tools, with many points of correspondence found the analysis extended understanding of possible designer activities in both spheres. A framework in the form of a table of the tool activities and related strategies was presented with the suggestion that this be accompanied with the real life example found in the designer interviews. How best to present the framework to designer-makers and how it could impact their practices would be a further piece of research. This research could incorporate giving or demonstrating the information in the form of a booklet, verbally, or as a workshop. Data on the impact on the designer's practice could be gathered through monitoring design processes and or interviews over a relevant timeframe. This work could supplement what has been learned so far and even find new knowledge about these models as potential pedagogical tools.

Stiny's rule schemas were found to be useful to model design-through-making processes. There may be other aspects of shape grammar theory that could be applied to making processes to reveal further insights into both. In particular the idea of shape schemas, as described by Woodbury [113] may be an interesting way of framing pieces of material and how material properties interact with tools to produce different shapes. It's likely from the complexity that Woodbury [113] found in shape schemas that this may be a challenging task to go further than the initial alignment made here.

In addressing shape grammar weights new definitions and formal extensions have been established for theory. These were collected by working through design scenarios with specific material properties related to two particular 3D printing systems. These experiments found that weights tools had to be tailored to each design process, with respect to the material properties, systems and design objectives. It follows that there may be further definitions to discover through carrying out further designer experiments to model and use other material properties and fabrication systems.

In this research the double head Objet Connex system and two accompanying materials were used to explore multi-material, multi-behaviour weights. Object offers a range of materials, with different properties, a range of colours, translucencies and flexibilities that can all be blended to form a wide range of secondary materials. Further work could investigate more of these materials and the possible combinations and computational making applications. Since this research was carried out Objet has developed a machine with three jet heads, allowing the blending of three materials at a time, introducing what would be a third weight component and an even wider array of possible materials and behaviours for this system, again with potential to yield more knowledge about computational making and shape grammar weights.

Section 11.3 discusses the possibility of representing material density patterns for 3D printed objects as weights, using weights to assign density patterns to shapes and provide calculations to manage the results of two over lapping shapes with different densities could be explored further. A huge array of different density patterns could be used and their related shape interactions, parameters, behaviours and applications are a potentially become a complex design problem that weights could help resolve through computational making design experiments.

13.6 Personal reflection

The author came fat this research from very much a personal standpoint. As a designer-maker I found design theory and research to be interesting and insightful, much of which I wished had been taught to me more conspicuously in my design education. However as a designer-maker I felt that although design theory discussed recognisable elements from my ways of working, I felt that certain aspects of my practice were not represented. Craft literature again offered some pleasing anecdotal descriptions and explanations of working with tools and materials that rang true, but in this area the more rigorous academic analysis of design theory was absent.

This research has enabled me to develop a language for my own use, a conceptual tool, if you will, for proceeding through my computational design and making processes. I feel I have a better understanding of how and why making process can unfold into creative outcomes. I have a range of tactics and strategies when it comes to my tools rationalised in my thoughts when I'm seeking creative outcomes, and a confidence that these are valid.

I hope that this research can offer other designers and researchers a similar insight into design-through making and support any endeavours to produce new, useful objects in imaginative and effective ways.

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The following notes were used in interviews with designers, they were not adhered to strictly as the interviews had in informal tone, but were used as a means to keep the conversation going and were in the most part all asked.

How would you describe yourself? (ie designer, maker, jeweller etc)

Where do you generally draw inspiration from?

Focus questions on a particular collection/body of work the designer has recently been involved in:

Description of the collection?

Was there a reason for designing this collection? (problem, brief, opportunity, idea etc?)

What if anything is 'new' about it?

What were the initial ideas and can you remember where they came from?

Did you impose any constraints on yourself? What were these?

How did the objects evolve – what were the similarities and differences between the initial ideas and finished products.

What were the reasons for these differences?

What are the main tools you used to make these items? (Tools in a loose sense, may also cover processes and materials if these were important)

How and why did you select these particular tools?

Did you customise these tools in any way? (unusual uses, make your own tools in anyway)

How did you find using the tools? (frustrations, limits, learning curves, flow experience, disappearing tools)

How much control do you have and want of your tools?

Were there any surprises, good or bad, from the tools? Did these influence the process or outcomes?

Do you sketch?

Do you prototype? How? (samples, tests?) What did you want to find out, what did you find out?

Do you make a lot of prototypes?

What small moves and decisions do you make throughout the process?

How much do these influence what you end up doing?

Do you stick to the initial plan?

Where did you find cues/departure points for variations?

How have/are you going to continue from this work?

How much has this work influenced the next project?

Do you have a lot of ideas? How many do you follow up and how do you decide if something is a good idea?