Seamless Knit – Dimensions Unfolding

An Investigation of 3-Dimensional Knitted Form-Building

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Abstract

This research investigated the latent 3-dimensional form-building capability of digital seamless knit technology with the intention of demonstrating the potential of knitted fabric within a new and emergent design dimension; one underpinned by 3-dimensionality, volumetric forms and tactile surfaces.

Developed for the knitwear industry in the mid 1990s, seamless knit technology emerged from radical technical innovation and enabled a new mode of textile production: complex 3-dimensional knitted forms could be fabricated in a single machined process. The technology's potential for innovative form and function beyond garment production is widely acknowledged. However, some 25 years later there remains uncertainty as to the attributes and parameters of this potential, particularly in the area of 3-dimensional non-garment form. The technology's positioning in an industrial knitwear environment and the format of its proprietary design interface have constrained access and understanding of its capacity, resulting in limited recognition or use of its unique capability as a 3-dimensional textile fabrication tool.

By means of a practice-led design inquiry, the research engaged in a conceptual displacement of seamless knit technology in its endeavour to extend knitted form beyond surfaces that mould and move around the body, to focus on those that enclose 3-dimensional geometric forms. The research was guided by an architectural form-building approach, using performative operatives in the systematic fabrication of 3-dimensional cubic geometric forms; configurations commonly referenced across domains such as architecture, industrial design and engineering.

Through this process, a knitted form-building methodology encompassing a cubic form-building system was established, suggesting an alternative way of thinking about knitted form that exploits the latent 3-dimensional fabrication capability of Japanese knitting-machine manufacturer Shima Seiki's WholeGarment knit technology. The system is supported through articulation of a cubic form-building domain that includes initial components for a 3-dimensional form library alongside a system of textual, symbolic and visual representations. Tools and resources have been developed to support the translation of 3-dimensional geometries into the knittable surfaces of the technology's 2-dimensional programming grid. A range of 3-dimensional cubic artefacts has been produced, providing physical representation of previously unrealised fabrication capability through easily decipherable objects.

The research and its findings demonstrate a space of possibility – of what could be – through new ways of approaching knitted form. More specifically, the research presents an alternative method of design with seamless knit technology, supported by a range of resources that allows the advanced 3-dimensional form-building capability to be accessed, understood and further explored by a broader range of design practitioners.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed: 

Date: 5 June, 2020

Intellectual Property Rights

The author retains the rights to the intellectual property of the artefacts, designs and processes outlined in this thesis.

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Glossary

Term	Definition
3-dimensional form	A broad category of 3-dimensional fabrication encompassing garment and non-garment forms.
3-dimensional geometry or geometric form	A 3-dimensional fabricated form consisting of planes that bound a geometric shape.
Attribute	Textual description and visual notations describing geometric shaping of an operative (category of geometric shaping).
Automatic software	An automatic software wizard within Shima Seiki's design system for the programming of knitted cloth or garments.
Bias knitting	A construction technique whereby planes are knitted on a diagonal. Refer to Appendix A, Construction Techniques, for further detail.
Bind off	A process of sequentially pulling stitches through to the adjacent loop such that the stitches are locked, and the bound edge cannot unravel.
Cable stitch	A stitch formed by adjacent loops crossing over each other. In fabrication of cubic geometries, it has been used to fill 'holes' where loops are pulled in opposing directions due to a change in plane or stitch direction, leaving a wider gap in the fabric.
Carriage	The mechanism that moves back and forth along the needle beds of a knitting machine, selecting needles and leading yarn within the fabrication space.
Composition	Geometric forms comprised of more than two operatives (categories of geometric shaping) through an extend process.
Compressed program	An abstracted knit diagram composed of packages of code, which when developed provides a knit program. (Shima Seiki 's term – compressed pattern.)
Course	A horizontal row of inter-looped stitches.
+ cube	An operative (construction technique) for cubic geometric form-building consisting of six equal planes, each perpendicular to adjacent planes.
Cuboid	A range of geometric forms consisting of six perpendicular planes, which could be all squares, all rectangles or a combination of both.
Design system	The system comprising the user interface for Shima Seiki's knitting technologies.
Developed pattern	Shima Seiki's term – the expanded version of a compressed pattern representing a knit program. In this format the program shows a high level of fabrication detail, including needles, stitches and carriage moves.
Fabricated form	Knitted 3-dimensional geometric form.

Flat-bed knitting machine	A weft knitting machine with needle beds arranged in a horizontal format with front and back beds parallel to each other.
Garment template design system	Shima Seiki's term – a set-up wizard for the design and production of seamless knitwear.
Half gauge	Gauge indicates the number of needles per inch in a needle bed. In this research the ability to knit at half gauge allows for knitted cloth to be constructed using loops on every second needle. Every other needle is then left empty, which provides capacity for shaping cloth, as empty needles enable the transfer of stitches and for loops to be held.
Held stitches	Stitches are held while knitted cloth is constructed in other areas of the surface. Also known as suspended stitches.
+ hinge	An operative (construction technique) for cubic geometric form-building defined as an independent component creating a join between two geometries.
Integrate	A process of sequential fabrication in which use of one operative follows the other.
Interlock	Two 1×1 rib fabrics knitted on alternating needles.
Knit Paint	The programming module within Shima Seiki's SDS®-ONE APEX3 design system.
+ ledge	An operative (construction technique) for cubic geometric form-building that uses perpendicular planes to extend or shorten cubic geometries.
Merge	A process of merging of two or more operatives to create a single programmed component.
Narrowing	The width of a knitted surface is narrowed during fabrication through the movement of stitches on top of adjacent loops.
Operative	A category of geometric shaping distinguishable by both construction technique and resultant form.
Option Lines	Shima Seiki's term – a programming structure that allows for construction parameters to be programmed against each course of knitting.

Package	Shima Seiki's term – a coded programming component in which each line of code represents a group of knitting instructions. These packages of code are used to create compressed patterns.
Parachute shaping	A narrowing technique that allows for even distribution of stitches across the width of a surface.
Process mapping	A mapping of front and back needle beds to 3-dimensional fabricated form.
Racking	The lateral movement of a needle bed.
Seamless knitting	A knit construction technique that creates a shaped seamless knit form.
SDS®-ONE APEX3	The design software component of Shima Seiki's digital knit technologies.
Short row	A shaping construction technique whereby increasing and/or decreasing the length of succeeding knitted courses creates a wedge within a surface.
+ spiral	An operative for cubic geometric form-building characterised by a rotational or twisting motion within a geometry.
+ swell & taper	An operative for cubic geometric form-building in which a triangular prism can be integrated within the surfaces of tubular knit rather than at its edge. This operative primarily uses inside widening and narrowing to increase or reduce the width of a plane.
Takedown	A mechanism to move the fabricated cloth away from the construction area by applying tension to the cloth.
Transfer stitch	The process of moving a stitch to another needle adjacent to it or on the opposite needle bed.
Tubular knitting	A circular knitting technique whereby construction on front and back beds creates a tubular fabrication.
Wale	A vertical row of inter-looped knitted stitches.
+ wedge	An operative for cubic geometric form-building defined as a triangular prism that can be integrated within the tubular knit or bias knit planes of cuboid fabrication.
WholeGarment	The trademarked name for seamless knit technology produced by Shima Seiki Mfg., Ltd, Japan.
Widening	The width of a knitted surface is widened during fabrication through the insertion of stitches on empty needles within a plane.

Chapter One

Positioning the Research

This research is positioned within a distinct textile fabrication environment, one that allows for a new mode of production in its capability to knit 3-dimensional form. This environment results from the radical technical innovation embedded in a category of industrial-scale garment manufacturing technologies known as digital seamless knitting technologies. Though the technology's potential for innovative form and function beyond garment production is widely acknowledged, some 25 years after it was first marketed there remains uncertainty as to the attributes and parameters of this potential, particularly in the area of 3-dimensional form building. This research is conducted in the design environment of Shima Seiki Manufacturing Ltd's WHOLEGARMENT® technology, referred to as WholeGarment in this thesis.

Guiding this inquiry is a conceptual displacement of WholeGarment knit technology, intended to diverge from and extend knitted form from those surfaces designed to mould and move on the body to those that enclose 3-dimensional geometric form. As such, the technology is framed as a 3-dimensional textile fabrication tool, for potential use within a broader design domain; a use underpinned by elements of 3-dimensionality, geometric form and tactile surfaces.

In accessing such potential, this practice-led research engages primarily with the construct of knitted form; giving consideration to new ways of thinking about form that allow for the integration of this new dimension in the fabrication of knitted cloth. This chapter gives background to the positioning of the research, with a focus on its significance alongside my background as the researcher, outlining the setting from which the inquiry emerges. The chapter concludes with a brief discussion of the structure of this text.

The Textile-design Landscape and Emerging Opportunities

Historically, the design and construction of knitted cloth has been split into two distinct academic disciplines – textile design and textile science. Textile design encompasses a range of practitioners from artists and craftspeople to designers and theorists. As a making practice, textile design is commonly focused on the expressive attributes of cloth, with consideration for visual and haptic elements and post-fabrication interactions. In this regard, designed knitted cloth is often produced as lengths of fabric to be used by other design disciplines for form building and application (Underwood, 2009). As knitted cloth is primarily used in the production of garments and accessories, it is also common to find crossovers and shared knowledge between textile and fashion disciplines.

By contrast, textile science is more technically focused, investigating the mechanical and functional properties of cloth. The field is broad-ranging, with aspects such as fibre properties, stitch formation, fabrication techniques and post-fabrication processes all contributing to the physical properties of the cloth. In the area of knitted textiles, the focus often operates at micro or stitch level, where aspects such as yarn and knitted loops are analysed as 3-dimensional structures within which fibre and forces combine to influence aesthetic, mechanical and functional properties of knitted cloth (Raycheva & Angelova, 2018).

In recent years there has been a shift in the knitted-textiles landscape, with a blurring of the traditional dualistic orientation between textile design and textile science. As such, knitted cloth is increasingly being considered as a whole, recognising that all elements, whether technical or aesthetic, are inherently linked within the construction process and directly inform the outcome. In Glazzard's recent research into auxetic knitted textiles, the author notes that the study "reacts to the segregation of knowledge and practice surrounding weft-knitted textiles, their design and applications…[and] challenges current disciplinary practices that divide knit into scientific, design and art areas" (2014, p. ii). Similarly, Underwood notes, "The developments and innovations occurring with materials science and textile technology are changing the way designers look at the relationship between surface and structure for the construction of form" (2009, p. 3).

Contributing to this shift is the rapid and sustained development of new fibres and technical yarns, and the development of advanced digital knit technologies and their capabilities. As these aspects evolve and converge, and the function and form of knitted textiles also evolve, knitted cloth finds itself in a position of new possibilities and new application within a broader design context.[1] Igoe (2010, p. 8) references the "phenomenal growth in innovative textile design work dealing with sophisticatedly complex problems."

Igoe (2010, p. 8) further notes that "textile designers are applying their knowledge and thinking to design for architectural, healthcare and wellbeing and automotive applications" while they work with "material scientists, engineers, chemists and industrial designers." Subsequently, we also see a transition in the role and attributes of the knitted-textile practitioner. Of particular significance to this research is the increasing use of digital knit technologies and the subsequent shift in the skillset of the knitted-textile designer (Smith, 2013; Taylor, 2015) as design practice and associated processes move into a digital domain.

It is within this evolving landscape that this inquiry is positioned; seeking to investigate and exploit an opportunity afforded by digital seamless knit technology and its capability to fabricate 3-dimensional textile form in a single machined process – capability that allows for knitted cloth to be used in new and innovative ways. The following sections provide a brief explanation of the distinct environment of digital seamless knit technologies, local utilisation and my background as the researcher, with the intention of highlighting the direction and significance of this research.

The Digital Seamless Knit Environment

The technology from which 3-dimensional fabrication capability emerged is designed for knitwear manufacturing in an industrial setting, and was first introduced in the mid 1990s by Shima Seiki Mfg Ltd. The technology is now available via two manufacturers[2] and, though initially slow to be adopted, has since been employed by garment producers globally due to its economic efficiencies (Choi & Powell, 2005). In particular, these relate to speed and quality of garment production, and the decrease in costs resulting from reduction in post-fabrication finishing requirements, including labour (Shaw, 2009; Yang, 2010).

Though effective in regard to operational efficiencies, seamless knit technologies have proven to be constraining in terms of creative output in the knitwear industry. Further, there has been limited recognition of the technology's advanced fabrication potential in non-garment application. This primarily results from the technology's garment-based design system and implementation in an industrial knitwear setting, which essentially masks its capability for 3-dimensional form building. As Black (2002) notes, "technological advances in knitting have at present outstripped the market's ability to absorb and utilise it."

Notably, the standardised use of seamless knit technology and limitations in its application are not fixed. However, while the significant unrealised potential is widely acknowledged, designers and manufacturers have faced difficulties in understanding the complexities of the seamless-knit environment and, subsequently, integrating it into innovative design and production practices

(Brownbridge, 2012; Smith, 2013). Within the knitwear industry, a focus on using the technology for cost reductions in high-volume, standardised garment production has also restricted opportunities for research, development and innovation. Outside the knitwear industry, there is limited access to the technology, making it difficult to investigate or demonstrate its capability.

As a result, 25 years on from its release to market, non-garment 3-dimensional knitted form-building remains a relatively unknown medium with minimal evidence by way of material artefacts to substantiate the extent of seamless technology's capability or illustrate its potential for sustainable and customisable textile production. Essentially, the introduction of a third dimension within a textile's fabrication, rather than post-fabrication, requires new understanding and process. In this regard, Black (2002, p. 256) notes that "new paradigms for knitwear design have to be acknowledged, accepted and acted upon and the three-dimensional aspects of design must be addressed," while Landahl (2015, p.19) further reinforces the need for "rethinking the foundations of the design process."

In 2019 Shima Seiki updated their marketing of digital knit machinery, noting, "More recently, our products have also been playing an increasingly important role in supporting manufacturing in other industries.... Therefore, under the new slogan 'KNITify the World,' we are proposing knitting as an alternative method for all things manufactured" (Shima Seiki, 2019, para. 2). While a promising sign of the transition of their technologies into a broader design domain, this change in market positioning has not yet translated to changes in its design system. As such, access to the reported non-garment applications remains constrained.

In the limited accessible research in this area, the primary focus is on knitted garments and improving engagement with seamless technology through technical literacy, or more specifically, knit programming knowledge (Igoe, 2010). By way of example, Smith (2013), Taylor (2015) and Radvan (2015) present design methods aimed at shifting knitwear design from the traditional 2-dimensional flat patterns embedded within the technology's design system to approaches that exploit its 3-dimensional fabrication capability. In the area of non-garment form, Underwood (2009) presents a Shape Lexicon derived from parametric design principles. Focused on architectural joins, which are difficult to produce by other means, the lexicon includes such forms as curves and tubular joins.[3]

There have also been some examples of innovative application in highly technical design outcomes, such as Nike's Flyknit sports shoe (Shaffer, 2013). Developments of this type have required significant levels of investment and often require collaboration with textile research centres and experienced knit technicians, reflecting both the technical expertise and investment of time currently required to exploit seamless technology's advanced capability. Further, much of the new knowledge generated through these developments is protected by commercial restraints and, as such, is not widely accessible.

The previous section outlines the environment contributing to a lack of awareness or understanding around non-garment, 3-dimensional form-building; an aspect that leads to the framing of this inquiry within the largely undefined domain of 3-dimensional knitted geometric form. More specifically, while the studies referenced above primarily highlight the need for a significant shift from established practices for design and construction in relation to knitted garments, the new form-building mode of knitted-textile fabrication with seamless knit technologies also offers significant potential across a broader design domain and a diverse range of applications. As such, the integration of a third dimension within knitted-textile form-building also presents the need for further representations, language and process; parameters with which to access and define a new form-building domain.

Local Context

The New Zealand knitwear industry has invested heavily in seamless-knit technology, noted by Shima Seiki agents in 2009 as having then invested in more seamless-knitwear machines per capita than anywhere else in the world (Smith, 2013). As is the case globally, the technology is primarily used in the production of high-end knitwear, most often differentiated through the use of unique, high-quality fibres such as merino and perino (a possum-fibre blend) for the tourist market (Kalyanji, 2013). This combination of technology and fibre has contributed to the preservation of an active local knitwear industry when many other manufacturing industries have moved offshore.

Within this local context, the Wool Taskforce Report noted the need for the wool industry to “collaborate and invest alongside the textiles industry to find innovative ways of adding value to products and to continue looking for new customers, new markets and new channels to those markets” (MAF Policy, 2010, p. 7). Further, one of the elements of New Zealand’s business growth agenda was to “further diversify into value-added, knowledge-intensive exports of both goods and services, to a broader range of markets” (New Zealand, 2017, p. 11).

Against this backdrop, this research is motivated by the significant potential for growth and innovation of the New Zealand knitwear industry, resulting directly from the advanced fabrication capability of its WholeGarment machinery. For example, the transition of knitted wool products into new markets could be supported through the fabrication of novel non-garment knit applications – essentially adding value to our fibre by focusing on high-end design outcomes targeted at niche global markets. Further, there is potential in AUT University’s Textile and Design Laboratory and New Zealand’s small-scale knit factories to support prototyping for research and development, both locally and internationally. Within this setting, the right combination of design and technical skills provides an opportunity for the export of design knowledge and intellectual property.

In this context, expanding knowledge of the potential of seamless knit technology and its form-building capabilities for the broader design and manufacturing industries is a key rationale for this research.

Positioning the Researcher

As the researcher in this practice-led inquiry, my background, skills and understanding have a direct influence on the pathway of the research. With specific reference to the framing of this inquiry, it is noted that the emphasis on non-garment form emerges primarily from my Master of Art and Design research (Kalyanji, 2013). During this study, immersion in the seamless knit environment at AUT University's Textile and Design Laboratory (TDL), and specifically the WholeGarment[4] environment, led to my improved programming knowledge and deeper understanding of the technology's construction process. Reaching a level of computational fluency[5] within this environment allowed a direct mode of engagement with the technology's programming interface and, significantly, the capacity to explore and understand the potential of non-garment knitted form.

Towards the end of that research I engaged with the concept of a knitted cube and the notion of knitting planes in perpendicular directions. At that time, I had only a crude understanding of the form and its construction, largely derived from replication of a Shima Seiki template for a knitted slipper (Kalyanji, 2013). Consequently, the non-garment forms created in that earlier research were limited to known textile objects such as seat and squab covers. Though I had a sense of the possibility within the domain of 3-dimensional form-building, my understanding of the construction of knitted planes was not at a level from which I could ascertain, or even suggest, what the breadth or format of that possibility might be. As such, this PhD research begins with furthering an advanced level of computational literacy. In addition, knitted fabrication of a cuboid is accepted as proven, and adopted as an entry point into the subsequent phases of research.

Figure 1.1

3-dimensional knit fabrication, couch squabs and cushion covers, Kalyanji, 2013.

Underpinning the practice and supporting an alternative perspective of the form-building potential of WholeGarment knit technology are both my positioning as a designer-maker and my lack of exposure to, or experience in, other means of knitted-textile construction. To explain further, understanding and engagement with my tools and materials is a critical aspect of my practice as a designer-maker. Dormer (1994) notes that for a craftsperson, materials, outcomes, and design are inseparable factors. With digital seamless knitting technology, opportunities in knitted cloth emerge directly from its fabrication, allowing for stitch, surface, shape and form to be fabricated simultaneously. This inseparability, and the potential to understand and exploit this distinct fabrication opportunity, is significant in the exploration and development of innovative design outcomes.

In addition, I have had no experience in hand knitting, or in knitwear design and, subsequently, bring limited knowledge around traditional knitted forms, or form-building process. This positioning has allowed for a perception of the technology with regard to what it can do, rather than what cannot be translated or fabricated in comparison to established knit practices and other means of knitted-textile fabrication.

Further influencing the path of the research is that the experience gained through my Master of Art and Design candidature (Kalyanji, 2013) allowed for independent access to the WholeGarment design system and machinery at the Textile and Design Lab in AUT University. In the setting of an unrestricted, self-directed exploration, away from the commercial constraints of industry, the research was constrained only by my own understanding, knowledge and technical skill; each of which expanded and unfolded through iterative design cycles as the research advanced. Alongside a relatively unhindered view of knitted 3-dimensional form and possibility, the self-directed nature of this practice was central to the methodology and findings of this research.

Aims and Objectives

Drawing from the positioning outlined in the previous section, this research seeks to explore and communicate the latent potential of digital seamless knit technology, primarily related to its capability to fabricate 3-dimensional cubic geometric forms. More specifically, the research objectives include:

- the generation of new knowledge and methods for conceptualising knitted form within a 3-dimensional fabrication environment;
- the investigation and demonstration of non-garment knitted form-building, specifically related to cubic geometric form;
- establishing a form-building system or library so that a broader range of practitioners can access and engage with seamless knit technology's 3-dimensional fabrication capability;
- the articulation of 3-dimensional cubic geometric forms through visual and textual languages.

Thesis Structure

This thesis documents the research inquiry as it endeavours to address the aim and objectives detailed in the previous section. The text is organised in two core parts. The first part, Chapters One to Four, provides a framing for the research. Chapter One introduces the research, providing a rationale for the study and highlighting the research aims and objectives. Chapters Two and Three outline the context from which the inquiry emerges. Recognising that the research engages with a specialised technology and is subsequently positioned within a distinct design environment, Chapter Two provides a background to the area of knitted textiles and, specifically, the WholeGarment knit environment. Chapter Three builds from this, reviewing the design of the technology's user software and its impact with regard to the current constrained application of seamless knit technologies. In doing so, opportunities for disruption and an alternative engagement with the technology are also revealed, providing a scaffold for the inquiry. Chapter Four considers the approach underpinning the design practice. Methods employed throughout the practice are outlined, with attention given to those used in the process of digital making within the WholeGarment knit environment.

The second part of the text, Chapters Five to Seven, documents and discusses the design practice and the research findings. Design practice, as the mechanism through which the research findings emerge, plays a critical role in this research. This element is addressed primarily through Chapter Five. In this chapter, design activity is outlined alongside technical findings and conceptual insights as they arose, allowing for the emergent path of the research to be revealed. The chapter unfolds through three key parts. Part 1 outlines three preliminary studies; interdisciplinary projects, knit as pliable topological surface and computational literacy. Each study adopted a different approach for engagement with the WholeGarment design process as the research sought to establish a means by which to access the 3-dimensional form-building capability of WholeGarment technology. The computational literacy study was extended, with attention given to the possibilities around the knitted cube. It is this study that formed an entry point into the primary pathway through the research. Part 2 outlines the operative form-building approach that underpins this study. The first section documents the development of a range of base cubic volumes, and the second presents the cubic form-building system that was established through this research. This system provides a context for Part 3 which turns to a more systematic investigation of cubic geometries as I endeavoured to define and populate a domain of knitted cubic geometric forms.

Chapter Six transitions into synthesis, analysis and dissemination of the research through the mediums of exhibition and a form-building manual. Initially intended as a means of dissemination, the exhibition served to further advance understanding of the practice as the convergence of conceptual and theoretical constructs and technical findings led to a consideration of language and representation for cubic form and associated fabrication processes. These insights resulted in the compilation of the research findings into a manual for knitted cubic geometric form-building.

Chapter Seven concludes the thesis with reflections and the identification of key research contributions to the understanding and exploration of 3-dimensional knitted form-building in the WholeGarment knit environment. Limitations of the research and directions for future inquiry conclude the discussion.

1 For example, the emergence of e-textiles as a field of study is supported within the knit environment by an increasing range of conductive yarns and the capability to integrate electronic circuits through digitally programmed intarsia knitting machines. Given the inherent drape and flexibility of knitted cloth, and this additional capability to embed sensory functionality within its fabrication, the knitted textile finds itself applied in areas such as health and physiotherapy (Otter et al., 2015).

2 H. Stoll GmbH & Co. KG in Germany and Shima Seiki Mfg Ltd in Japan.

3 Underwood's (2009) work is significant in its comprehensive documentation of non-garment knitted form-building. That research was used prior to this inquiry as an introduction to understanding and accessing the non-garment design capability of seamless knit technology (Kalyanji, 2013).

Chapter Two

Fabrication of Knitted Cloth in a Digital Knit System

The context in which knitted cloth is designed and constructed is in a continual state of transition as advances in technology and materials offer new perspectives in the cloth's form and function. This research explores the opportunity afforded by one such transition – the 3-dimensional fabrication capability of digital seamless knit technologies. As such, the research is grounded in a specialised digital fabrication environment in the field of textile design. Given the specialised nature of the subject matter, this chapter provides background to the research, with a brief overview of the design and construction of knitted cloth, the emergence of a distinct digital knit system, and its masked 3-dimensional fabrication capability.

Design and Construction of Knitted Cloth

There is an inherent complexity in the design of knitted cloth, due to it being a constructed textile[6] whereby its characteristics, defined by both aesthetic and mechanical attributes, emerge as interconnected elements within its fabrication. That is, those elements that constitute the cloth's materiality – its visual, haptic and functional properties – are intrinsically linked to its construction. As such, integral to the design of knitted textiles is an understanding of its construction.

In its most elementary state, knitted cloth is constructed from the continuous looping of a length of yarn. Construction is initiated by looping yarn around a needle to form a single stitch, and formation of adjacent loops creating a row of stitches. The technique advances through repeated movement back and forth across the width of the cloth as yarn is looped through existing stitches to create each additional row. As construction progresses, horizontal and vertical links materialise within the cloth, yielding the drape and pliability that characterises knitted textiles (Figure 2.1).

Embodied in the structural foundation created by this uninterrupted path of interlocking loops are numerous variables that can be manipulated into a seemingly endless range of knitted textile designs. For example, assorted textural structures and yarn types, and fibres with varying functional attributes can all be embedded in the layers of knitted cloth's stitch-by-stitch construction.[7]

Though yielding vast design potential, the many variables layered within knitted cloth are also a source of complexity, inextricably linked to each other, such that they must be resolved concurrently within each loop. Consequently, with aesthetic and technical design of knitted cloth emerging through the determination of numerous variables, there are many elements requiring simultaneous consideration (Studd, 2002; Glazzard, 2012).

Integration of Form

Adding to this complexity is the integration of form and the corresponding "interplay between shape and fabric" (Eckert, 1999, p. 3). From a design perspective, the fabrication of knitted form emerges from the looping of yarn into stitches, the duplicating of stitches into textured 2-dimensional surfaces and the manipulation of these surfaces into 3-dimensional forms. As detailed in Figure 2.2, there are three key methods in which surfaces are shaped into knitted form. Within these methods the aspect of form transitions from being a post-fabrication manipulation to being wholly integrated within the cloth's construction.

Alongside this, as form integrated into fabrication, the number of variables requiring simultaneous consideration increases, adding further complexity to the knit design process. Landahl (2015, p. 19) writes that the “symbiotic connection between form and material” is fundamental to the understanding of knitted-textile design. However, as Landahl (2015) also notes, there is a lack of literature or research acknowledging this connection, probably due to the complexity of the relationship.

Seamless Knit Technology

The seamless knit fabrication referenced in Figure 2.2 represents a significant shift in knitted-textile production, embodying a fundamentally different concept of design and construction in comparison to other flatbed digital-knit technologies. It is in this fabrication environment that this research inquiry is positioned and as such this section outlines the environment in more detail, starting with the launch of seamless knit technologies in the mid-1990s before outlining current application, research and development in both garment and non-garment form, and recent technological developments. The section ends with a more detailed discussion of seamless technology’s 3-dimensional form-building capability.

The knitting of tubular form has a long history, dating back to the hand-knit technique of ‘knitting in the round.’ This technique uses multiple needles, which are structured into a shaped rim or frame. Each row of stitches added to the frame increases the length of the tube. With this technique the tube can also be shaped and was commonly used to hand-knit caps, stockings and gloves (Black, 2012). The realisation of this concept in a mechanised format, in line with a long-held industry ambition to machine-knit complete garments, has resulted in numerous technological developments centred on the shaping of knitted cloth (Landahl, 2015, p. 20). For example, the first stage of seamless capability was demonstrated by Stoll’s pioneering approach, with the control of individual needles allowing the development of electronically controlled flat-bed knitting machines with individually selected needle capabilities (Black, 2012).

Seamless knitted form was first realised in 1970 by Japanese machine manufacturer, Shima Seiki Manufacturing Ltd., in its fully automated flatbed glove technology. In contrast to knitting in the round, in which the textile form is constructed in a visible, 3-dimensional space, the glove technology was developed from weft knitting machinery with parallel needle beds just millimetres apart. This disconnect between flat-bed configuration and the construction space of 3-dimensional form means form is difficult to perceive visually or spatially; an aspect that has a significant impact on this study and which is addressed in further detail in Chapter Five, Parts 2 and 3. Of particular relevance to this research is the capability to knit and merge parallel tubular forms within a single-machined process.

The evolution from gloves to large-scale garments, illustrated in Figure 2.3, was a lengthy process, triggering radical innovation of mechanical componentry.[8] When this highly anticipated technology eventually launched it was considered a new platform for creative capability and an exciting way forward for the knitting industry (Hunter, 2004b; Mowbray, 2004).

There are two primary manufacturers of digital knit technology, both of which introduced their seamless knit technologies in in the mid-1990s; Shima Seiki Mfg., Ltd. in Japan in 1995[9] and H. Stoll GmbH & Co. KG in Germany[10] in 1997 (Black, 2012). Though the seamless knit technologies of both manufacturers contain numerous patented elements and utilise their own proprietary software and programming languages, their machinery is categorised within the same class of technology and uses comparable seamless knit construction principles (Choi & Powell, 2005). As such, the findings of this research are expected to hold relevance across the category of technologies. However, it is through direct engagement with Shima Seiki's WHOLEGARMENT® technology[11] that this research unfolded. Accordingly, the discussions in this thesis specifically reference the attributes and environment of Shima Seiki's WholeGarment knit system, outlined in further detail in the following sections.

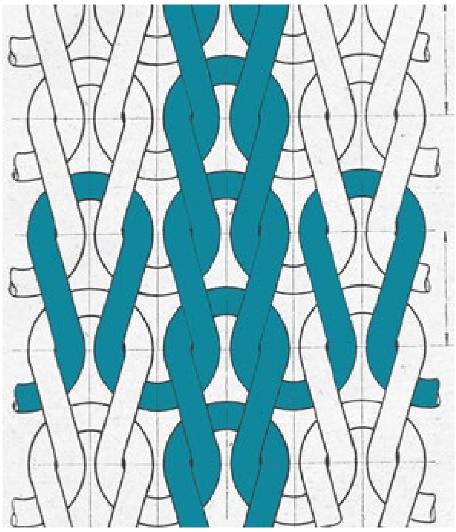


Figure 2.1

Looped construction of knitted cloth highlighting the horizontal and vertical links formed in the fabrication of cloth.

Adapted from Single knit structure, by Elkagye, 2014, Wikimedia Commons.

Retrieved from https://commons.wikimedia.org/wiki/File:Single_knit_structure.jpg

CC-BY-SA 3.0.

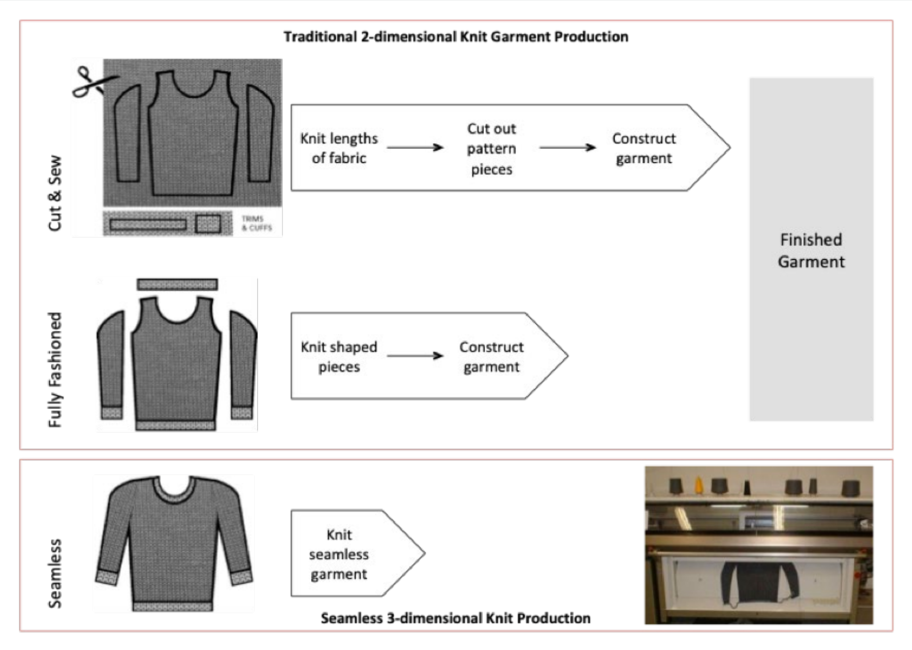


Figure 2.2

Knitted textile construction and the integration of form.

Knitted cloth is most commonly produced as a length of fabric. The cloth is then manipulated post-fabrication through processes such as linking and sewing to create 3-dimensional products such as garments in a process known as *cut-and-sew*. While the element of form may be considered among the decisions relating to aesthetic and technical attributes of the knitted cloth, in this process the cloth's end form does not materialise from the construction process itself, but from a subsequent structuring of the cloth.

In contrast are two knit-fabrication processes in which form is integrated first partially, and then fully, within the cloth's construction. The first, commonly referred to as *fully fashioned*, utilises a range of stitch structures and knitting techniques to widen or narrow rows of knitted stitches such that 2-dimensional textile surfaces are shaped as they are constructed. As in cut-and-sew, the cloth emerges as a single flat surface and is reliant on post-fabrication processing to create a 3-dimensional product.

In the last process, *seamless knitting*, form is fully integrated within the fabrication process through a tubular knitting technique. As such, 2-dimensional surfaces and 3-dimensional form are fabricated in the same process with shaping integrated into the tubular form as it is constructed. A more detailed explanation of this process is provided by Choi and Powell (2005) and Yang (2010).

Figure 2.3

Evolution of WholeGarment technology, development from flatbed glove to seamless sweater.

Retrieved from https://www.shimaseiki.com/wholegarment/

Shima Seiki WholeGarment Technology

Shima Seiki's WholeGarment technology (Figure 2.4) is primarily marketed for industrial-scale garment production in the fashion industry and as such is promoted for speed and quality of garment production in seamless forms, while allowing for creative outcomes (Power, 2007). The commercial benefits of the technology emerge from its capability to fabricate complete seamless garments including integrally knit technical features such as pockets, necklines and ribs (Figure 2.5). As a result, both labour requirements and excess material are reduced in comparison to methods of post-fabrication make-up such as cut-and-sew. Combined with virtual sampling capability, and inventory and distribution software for efficient stock management, the reduction in material waste is said to improve sustainable garment production (Shima Seiki, n.d.). However, though effective in the economic efficiency it offers, it has been noted that the technology constrains aesthetic expression and innovative design (Hunter, 2004b). Further, the complexity of WholeGarment technology's design process can result in increased sampling, and subsequently increased costs in both time and materials.

Application in the Knitwear Industry

As intended by Shima Seiki Mfg., WholeGarment knit technology is primarily adopted in industrial garment production for economic gain. The cost reduction resulting from elimination of garment make-up provides local knitwear manufacturers a degree of competitiveness against low-cost, offshore producers, while allowing direct engagement in quality control and responsiveness to consumer needs (Mowbray, 2002).

However, for many manufacturers the technology has not delivered on its promise of creative capability. Utilisation of the technology in innovative or novel garment designs has been constrained by a new and distinct fabrication technique accessed through a proprietary and unfamiliar CAD system. Currently the only known means of engaging with the technology, this CAD system essentially draws the design element of knitwear manufacture into a digital workspace. As a representation of the advanced capability of the technology this workspace is directly connected to the operation of the machines and has thus largely become the domain of the knit technician (Hunter, 2004a; Challis, Sayer & Wilson, 2006; Smith, 2013).

In New Zealand, industry endeavours to increase design value and differentiate garments have focused on the use of luxury fibres such as alpaca, possum or merino, targeting a high-end customer or luxury tourist segment; however, garment silhouettes in such production remains standardised (Smith & Moore,

Figure 2.4
Shima Seiki WholeGarment machine, AUT Textile Design Laboratory, 2018.

Figure 2.5
Shima Seiki WholeGarment samples.
Retrieved from https://www.shimaseiki.com/images/wholegarment/btoc/top2.jpg

2015). Similar outcomes have been reported by researchers in the United Kingdom (Challis, Sayer & Wilson, 2006; Brownbridge, 2012).

The environmental gains of WholeGarment knit fabrication do not appear to play a significant role in the adoption of the technology, or influence consumer spending (Smith, 2013). Shima Seiki USA Inc. sought to raise consumer awareness of the environmental benefits of WholeGarment technology with the launch of its Kotoba brand of knitwear in 2012. Marketed for its cutting-edge, locally produced, eco-conscious garment production, the brand worked closely with expert technicians at Shima Seiki headquarters in Wakayama, Japan, in designing its range of contemporary knitwear. Despite this arrangement, the range reflected fairly conventional 2-dimensional garment silhouettes based primarily on traditional cut-and-sew patterns, and the brand had ceased operating after a couple of years (ECO FASHION TALK, 2012).

Also restricting creative application of WholeGarment technology are the perceived constraints of the tubular knitting technique in relation to integration of colour, pattern and texture within the cloth's fabrication. In both industry and research, seamless garments are most often produced in single-colour fabrics with minimal, if any, textural patterning. These constraints around the cloth's visual and haptic attributes are often referenced in comparison to more traditional methods of knitted textile design (Mowbray, 2002; Challis, Sayer & Wilson, 2006; Knitting Industry, 2009a). However, patterning possibility has been shown to exist, as seen in Figure 2.6, and simply needs further exploration and alternative design approaches (Mowbray, 2002; Challis, Sayer & Wilson, 2006; Smith et al., 2014).[12]

Developments in Technology

Knitting-machine manufacturers have invested significant resources towards advancing their flatbed knit technologies, generally targeted towards increased specialisation or increased efficiency. For example, Shima Seiki's release of an 'inlay' knitting machine (SRY123LP/183LP) in 2013 allows for a weave effect within knitted cloth, resulting in a more rigid textile and new design potential, both visually and functionally. In their WholeGarment series, improvements and innovations have included machines mounted with four needle beds, which extend design and patterning capability (MACH2®X), and the introduction of the R2 (Rapid Response) CARRIAGE® System, offering significant gains in productivity as a result of faster knitting speeds and quicker carriage returns (Knitting Industry, 2009b).

Shima Seiki's CAD design system has also been continually developed and includes improved help menus and simulations to support learning. More specific additions have been made in areas such as virtual textile sampling and 3-dimensional garment visualisation. More recently, the company has also expanded into complementary business areas such as production planning and distribution, supported by the launch of their Product Lifecycle Management Software (PLM) in 2017. As a system targeted towards management of the entire manufacturing process for knitwear, from planning to production, this development reflects a sustained focus on industrial garment production (Apparel Resources, 2017).

However, the relaunch of Shima Seiki's website in June 2019 indicates a response to industry application with reference to the increasing role their knit technology plays in a broader range of manufacturing industries, including sports/outdoors, shoes and accessories, healthcare, home furnishings, automotive, aeronautical and industrial materials (Shima Seiki, 2019a). While most of the examples provided of these new product areas are still garment based, the website does show a small range of non-garment samples centred around home furnishings and automotive seating. It is difficult to assess the fabrication techniques used in these samples, or whether WholeGarment's 3-dimensional capability is being optimised.

Notably, in relation to this research, there have been no significant developments in the programming of non-templated form for WholeGarment fabrication, nor does there appear to be any suggestion of the technology's format becoming less restrictive or the company becoming more open to collaboration.

In contrast, Stoll has had an early focus on non-garment forms and technical textiles,[13] with technology developed for applications such as upholstery and medical textiles (Black, 2012; Stoll, n.d.). Though these technologies do not always employ seamless knitting techniques, they do offer broader applications for knitted textiles. Stoll's openness to alternative approaches is also demonstrated through the customisation of their technology for developments such as Nike's Flyknit running shoe (Shaffer, 2013) discussed in further detail in Non-Garment Forms.

Also of interest in regard to developments in technology is Kniterate. Developed from an undergraduate project undertaken in Barcelona in 2013, the concept of affordable and compact digital knitting machines emerged in response to the inaccessible cost and size of digital knitting machines, in comparison to easily accessible means of fabrication such as 3-dimensional printing. The first Kniterate machines, produced in China, were shipped to customers at the end of 2019 (Kniterate, n.d.). While these machines do not offer the same capability as seamless knit technologies, they allow for increased access to a digital knit environment and have the potential to disrupt current systems of use.

Research and Development, Academia and Industry

In this section, recent research and development stemming from the application of seamless knit technologies is outlined. While some of the more innovative research and applications are not accessible,[14] due to commercial confidentiality, the discussion below provides a brief review of garment forms, non-garment forms and the area of technical knitting as a context for the environment in which this research is positioned.

Garment Forms

Research and development related to seamless knit fabrication is predominantly focused on the manufacture of knitted garments. Challis, Sayer and Wilson (2006, p. 41) note that the technology "forces a conceptual shift in the way knitted garments are designed and created," requiring understanding of 3-dimensional design concepts. Varied findings have been published in addressing these concerns. Some researchers have offered new design approaches recognising that the traditional flat fabric panels devised for seamed construction are no longer a necessity (Evans-Mikellis, 2011; Landahl, 2015). In other research (Figures 2.7-2.9), variation in Shima Seiki's prescribed garment silhouettes is demonstrated through adaptations in stitch structure, volume or design features (Yang, 2010; Gover, 2010; Smith, 2013; Taylor, 2015; Radvan, 2013).

In designs deriving from adaptations of prescribed garment templates, the notion of improved technical literacy is key, essentially allowing the designer a more direct engagement with the technology's advanced capability. Improved technical literacy is also key within the approach adopted for this research and is discussed in further detail in Chapter Five, Part 1.

Non-garment Forms

For much of the 25 years since the introduction of seamless knit technologies, research and application of non-garment form was virtually non-existent. A lack of recognition or understanding of the technology's unique mode as a 3-dimensional textile fabrication tool meant little consideration was given to new design possibilities, and as a result there were limited examples of 3-dimensional form-building or research concerning this mode of fabrication.

While there has been a significant shift in interest and application in this area more recently, many of the developments sit within research and development arms of commercial sectors, backed by significant investments of time and technical expertise, and protected by patents. As such, there are limited means

Figure 2.6

3-d Knit Transformations, Smith, Kalyanji, Fraser (2014) demonstrate WholeGarment patterning possibilities.

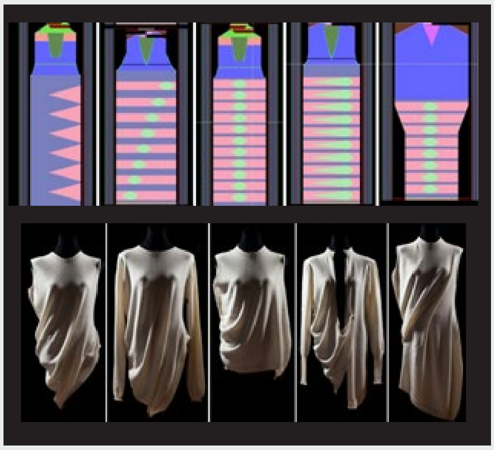


Figure 2.7

Seamless knitwear: Singularities in design. Smith (2013) develops a technique to use wedge-shaped packages to create directional changes in knitting.

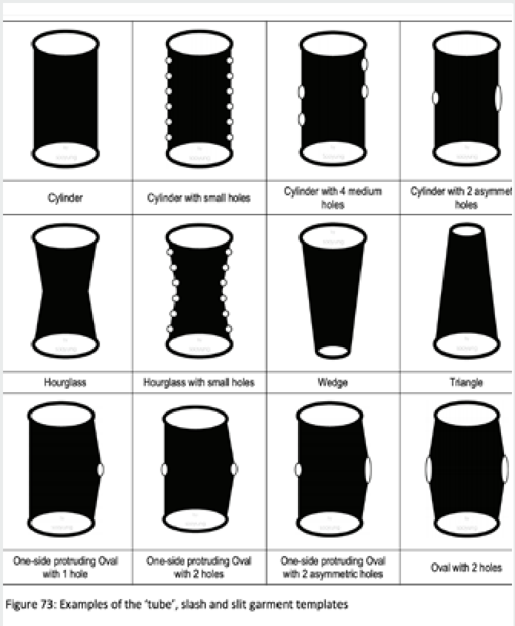


Figure 2.8

A creative journey developing an integrated high-fashion knitwear development process using computerised seamless v-bed knitting systems. Yang (2010) establishes seven methods for designers to engage with digital garment interface, one of which is shown in this image.

Figure 2.9

The technical designer: A new craft approach for creating seamless knitwear. Taylor (2015) adopts a craft-based approach in the programming of seamless knitwear, in presenting the case for design and technical aspects of knitwear to be reunited.

by which to view or evaluate the incidence, form or effectiveness of these developments, and the opportunity to further understanding of this advanced form-building capability is restricted.

Of the known commercial developments in this area, perhaps the most commonly referenced are innovations in technical footwear. Shaped knitted uppers have been developed by a range of high-end sportswear brands, including Nike, Inc., and Adidas AG.[15] Though not necessarily seamless or 3-dimensional as they come off the machine, seamless technology's advanced shaping capability is used to produce these complex one-piece patterns.[16] In addition, the shaping of the uppers is reinforced by the technical attributes and stitch structures of specialised yarns integrated in their fabrication. This effectiveness of combining advanced fibres, structures and shaping to embed support, strength, flexibility and form into the fabrication is such that postproduction fills or frames are not required.

The concept of the one-piece pattern, and the ability to shape tubular forms, has led to a range of innovative applications of seamless knit technology,[17] demonstrating a shift in the application of the seamless knit technology from traditional 2-dimensional design and constructions. In these approaches the properties of knitted cloth are exploited, using its characteristic as a pliable surface to produce tactile, formable surfaces – most notably in comparison to 3-dimensional solid-state printed objects. As seen in Figures 2.10 and 2.11, complex transitions in texture, stitch, yarn and knitting direction can be incorporated simultaneously into the construction of the cloth.

While such product lines demonstrate both the complexity and possibility in non-garment fabrication (Fischer, 2016; Shaffer, 2013), lengthy development times are also indicative of the significant investment of resources and expertise required in such prototypes. For example, Nike, Inc. has been working on iterative developments of their Flyknit shoe for over 20 years. Further, the fabrication of the knit components of these products falls into the category of technical textiles. As the findings of this research are likely to be applied in this area, the field of technical textiles is discussed further in the following section.

Within the academic area, Underwood's (2009) research is significant for its introduction and exploration of 3-dimensional geometries, as seen in Figure 2.12. Approaching the technology from an architectural perspective, the author demonstrates the application of parametric design representation, covering a range of knitting techniques in both seamless and one-piece patterns. As a result, Underwood's (2009) shape lexicon provides a guide to form-building geometries such as cones, domes, tubes and tubular connections, focused around architectural joins and shapes difficult to produce by other means. This research is discussed in further detail in Chapter Three, Package Adaptation System, in relation to methods developed for 3-dimensional knitted form-building.

Technical Knitting

Particularly relevant with regard to non-garment form is the area of 'technical knitting.' A specialised area of knitted textile design, technical knitting is considered to operate at a micro or stitch level in its consideration of design, construction and fibre, using advanced knitting technologies to achieve specific form and functional attributes in the fabrication of knitted products. As the form and function of knit transitions into alternate applications and domains, the area of technical knitting is expanding. As Colchester, cited in Underwood (2009, p. 10), notes, "We are living through a period of unprecedented material innovation that looks set to change the role and purpose of fabric in our lives."

Yarn, as the material from which a knitted form is created, plays a significant role in the form's success, in that the form's functionality is dependent on the specific attributes of the yarn. In applications of technical knitting this is commonly observed in areas such as e-textiles, where the form relies on the conductivity of yarns to integrate electronic circuits within a knitted form, or in advanced accessories such as Nike's Flyknit shoe upper (Figure 2.10), discussed above. As such, the material and functional qualities that technical knitting brings to the fabrication of knitted textiles further extends the possibility and potential that knitted form-building can offer to other disciplines.

3-Dimensional Knit Fabrication

Within its traditional setting of garment manufacture, the 3-dimensional capability of WholeGarment knit technology is often referenced in relation to the knitting of shaped seamless tubular forms as opposed to the more traditional shaped 2-dimensional flat fabric. Further, references to the technology's advanced design capability tend to address the capability to integrally knit features such as pockets and trims – features that are still designed as replications of traditional flat 2-dimensional knitwear patterns.

Underwood's (2009) work demonstrates an additional facet to the notion of 3-dimensional capability in its development of 3-dimensional knitted geometries. Recognising that the distinct and complex nature of the WholeGarment knit environment can be difficult to comprehend and that there is limited research or application in this area, the technology's 3-dimensional fabrication capability, as defined for this research, is outlined here in further detail.

Figure 2.10
Nike's Flyknit running shoe.
Retrieved from https://www.innovationintextiles.com/nike-fly-knit-a-seamlessly-knitted-running-shoe/

Figure 2.11
Benjamin Hubert's Tent Chair for Moroso.
Retrieved from https://layerdesign.com/project/tent/#top-page

Figure 2.12
The design of 3D shape knitted preforms, Underwood, 2009.

In WholeGarment technology the capability to knit shaped tubular forms results from a mechanical arrangement in which knitted cloth can be constructed at half-gauge – that is, tubular forms are constructed through the forming of loops on alternate needles, leaving an empty needle between adjacent loops of knitting (Figure 2.13). The empty needles essentially represent the additional capacity offered by the technology in that it allows for knitted loops to be transferred between front and back needle beds, and subsequently, for loops to be shifted systematically along a single bed. This movement of loops is integral to the shaping of tubular forms and, in the case of seamless garment construction, allows for tubular sleeves to be knitted parallel to a tubular body in advance of being integrated at the arm-hole.

These empty needles are also representative of the capability to knit 3-dimensional geometries, in which stitches – or planes – can be constructed in different directions. Construction of such geometries relies on an ability to hold knitted loops at the edge of a fabricated plane such that another plane can be integrated above. It can be seen that though the capability to knit 3-dimensional geometries and seamless knitwear results from the same mechanical arrangement of the knitting machine, the design and construction of the two differ considerably.

In this research, this differentiation and the use of the phrase 3-dimensional geometry in relation to cubic forms is characterised by:

- Use of held stitches to knit planes in different directions
- Forms that contain a minimum of six planes post filling or framing
- Surfaces that can enclose 3-dimensional volume
- Fabrication as a 3-dimensional form as opposed to a one-piece pattern that can be laid flat

3-Dimensional Knitting in Relation to 3-Dimensional Printing

Outside of the textile field, seamless knit technologies are sometimes described as a form of 3-dimensional printing (Fischer, 2016; Raycheva & Angelova, 2018). Both fabrication technologies are categorised as additive manufacturing tools able to be used in the prototyping or industrial production of 3-dimensional forms. However, fundamental differences in fabrication methods, materials and user systems result in significantly different design environments for each technology.

Figure 2.14 details some of the key differences between the technologies. While the focus is on those aspects that give WholeGarment knit technology a different functionality and product in comparison to 3-d printing, the list also serves to reinforce the distinct nature of the 3-dimensional knit environment.

Perhaps most significant is the difference in the fabrication itself, both in terms of the construction space and the materials used. Where 3-dimensional printing operates in a 3-dimensional site to fabricate solid-state forms, 3-dimensional knitted form is tensile, constructed on parallel needle beds just millimetres apart to fabricate tactile, flexible surfaces.

More specifically, the solid state of 3-dimensional printed objects generally results in self-supporting objects, while the 3-dimensional form of a knitted object is realised only when its knitted surfaces are filled or framed. Further, expression of visual and haptic aesthetic within the process of 3-dimensional printing is limited, though the solid state of printed objects allows for a range of post-fabrication surface designs to be applied. In contrast, colour and texture are embedded in the knitted surfaces of 3-dimensional knit fabrications.

The differing construction spaces of the two technologies are particularly relevant in this research as the construction of 3-dimensional knitted forms between parallel knit beds is a source of complexity in the knit environment. In the print environment, a 3-dimensional object is fabricated in a 3-dimensional construction space. In the fabrication of knitted forms between parallel needle beds, it is difficult to perceive the 3-dimensional form within the construction space, requiring a difficult mental translation between 3-dimensional form and 2-dimensional fabrication. This translation emerges as a key concept in this research, with the complexity of the translation impacting on both the realisation of 3-dimensional knitted forms and on the understanding of potential within the 3-dimensional fabrication domain.

Related to both construction space and material is the fabrication technique of each technology. Though both work as additive processes, building upon layers of substrate or stitches to construct form, the 3-dimensional print head is able to move freely around the construction space in such a way that fabrication can be stopped in one place and continued in another. In contrast, the carriage that holds the yarn in knit fabrication can only move left and right along the needle beds. As knitted form emerges from the continuous looping of yarn in this back-and-forth motion, the manually programmed sequence of construction is critical to the viability of the fabrication.[18]

The final aspect in which these technologies significantly differ is in their operating systems. The unique encoded programming language and proprietary format of WholeGarment's technology is detailed further in Chapter Three, WholeGarment Design System. In contrast, software for design and construction of 3-dimensional printing is easily accessed and uses program formats that are interpretable by a range of software and technologies.

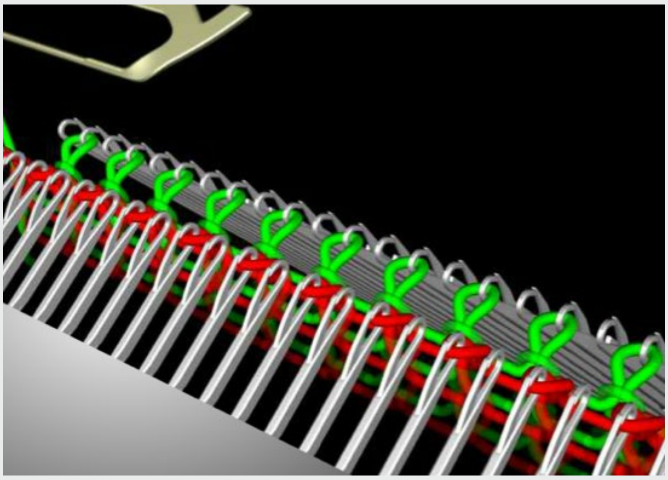
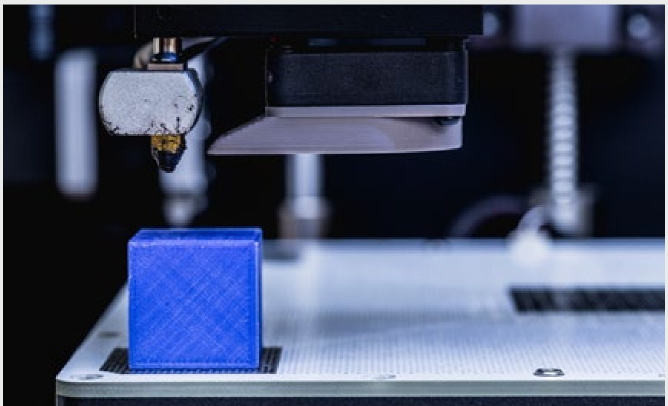


Figure 2.13
Half-gauge knitting, showing a spare needle between adjacent loops. Shima Seiki Design System (2019).



3-Dimensional Printing

- widely available software
- can program or visualise in 3-d software
- production in 3-d space
- materials used are composites
- produces solid-state object
- generally single tone, single material in one form

3-Dimensional Knitting

- proprietary, unique software
- programming interface in 2-d grid
- production on parallel needle beds mms apart
- materials used are textile fibres as yarn
- produces flexible and malleable textile
- multi-tone, multi-yarn in one form

Figure 2.14
Comparison of 3-dimensional printing and 3-dimensional knitting, 2018.

With regard to innovative design and application, 3-dimensional printing benefits from the broad accessibility of its software and technology, which facilitates both skill and knowledge acquisition and ease of prototyping and production. In addition, 3-dimensional forms are easily visualised within the format of its software, allowing for exploration, experimentation and refinement within a digital space. These factors combine in the realisation of a broad range of innovative design outcomes. The limited representation of innovative 3-dimensional fabrication within the WholeGarment knit environment hinders development, as there is no sense of 3-dimensional possibility within this space; an aspect addressed in this research.

While 3-dimensional print and 3-dimensional knit can both be categorised as additive fabrication technologies, the significant differences in fabrication techniques and materials between the two suggest it is problematic to indicate they are similar.[19] As the more widely recognised technology, it is 3-dimensional printing that is most often referenced as a way to explain 3-dimensional knit technology, subsequently implying a capability of the technology that is unattainable and likely to disappoint. To explain further, if the expected functionality of 3-dimensional knit is inaccurately assumed as the same as that of 3-dimensional print, one is likely to come up against numerous iterations of what is not possible before a viable solution is reached. In contrast, this research is motivated by the notion that greater understanding of 3-dimensional knit capability and demonstration of its potential would allow for 3-dimensional form-building to be considered through an alternate lens and subsequently applied in innovative design outcomes.

Summary

This research is positioned to investigate an opportunity afforded by the advanced 3-dimensional fabrication capability of digital seamless knit technologies. As such, this chapter provides a background to this technology, outlining its evolution, application and research in both garment and non-garment forms, suggestive of the technology's current system of use. In addition, as the area from which this research draws, the 3-dimensional fabrication capability of the technology is also detailed.

While the technology has been available for some 25 years, it remains largely unexplored outside garment design, with little understanding and demonstration of its advanced fabrication capabilities and areas of application. In the following chapter, constraints and limitations of the current use of seamless technologies are addressed in further detail. Emerging from this discussion are conceptual and theoretical constructs that inform the approach adopted for this research as it seeks to explore and demonstrate 3-dimensional form-building potential through an alternative engagement with digital seamless knit technology.

4 Further explanation of Shima Seiki Mfg. Ltd's technology and its operational environment can be found in Chapter Two, Fabrication of Knitted Cloth in a Digital Knit System.

5 The reference to 'fluency' is made specifically per Smith's (2006) levels of computational use described in Chapter Three, Computational Flexibility.

6 With regard to the broader textile-design field, both knitted and woven cloth are categorised as constructed textiles. In contrast, textile-design processes such as print, dye and embroidery are applied to the surface of a constructed cloth and can be categorised as surface design.

7 For further discussion on the variables in knit construction see Brackenbury (1992) and Spencer (2001).

8 For a more detailed account of the development of seamless knit technology, its mechanical attributes, and associated construction techniques see Power (2007) and Choi & Powell (2005).

9 Shima Seiki Mfg., Ltd.'s models of seamless knit machine are called WHOLEGARMENT® machines, with the latest series being the MACH2 Series.

10 H. Stoll GmbH & Co. KG's models of seamless knit technology are Knit & Wear®.

11 Referred to as WholeGarment technology for the remainder of this text.

12 From a textile-design perspective, the integration of visual and haptic aesthetic within the cloth's fabrication was not given significant attention in this research. This was due to both time constraints on the research and a focus on form as a design element. However as noted in Chapter Five, Part 2, Materials and the Translation of Surface to Volume, as the exploration of 3-dimensional forms unfolded it became evident that changes in stitch directions and knitted planes were most visible in a single colour, plain knit textile, leading to the decision to knit artefacts in a neutral grey shade of wool.

13 Technical textiles are discussed further in a later section.

14 Academic research is primarily focused on fashion knitwear. While the technology is also used in the development of garment-based forms, in areas such as healthcare, findings are often reported in relation to the field for which the product is developed and, as such, has limited reference to the fabrication of the knitted textile components. Further, while there are a few examples of innovative non-garment form in industry, much of this research is also protected by commercial business structures.

15 Nike, Inc., produces shoes with knitted uppers in its Flyknit range, and Adidas AG produces their range under the name Primeknit.

16 The concept of a one-piece pattern describes a shaped textile form that can be manipulated post-fabrication with minimal seams or joins into a 3-dimensional product.

17 As examples, see Bejamin Hubert's Tent Chair and Cradle collection, Ikea' s PS 2017 armchair, Ulysse Martel's KnitGuard and Jonas Forsman's Shift chair. Smith and Moore (2019) provide further examples of non-garment knitted forms.

18 This characteristic of the fabrication technique is referenced throughout Chapter Five, Part 3.

19 'Is 3D knitting worth it?' (Huffa, 2017) provides further discussion of the differences between 3-dimensional knit and 3-dimensional print, highlighting the complexity of design and production within the 3-dimensional knit environment while highlighting the unique benefits.

Chapter Three

Research Context

Though the design of knitted textiles is an historical practice, its emergence as an academic discipline is much more recent and as Igoe (2010, p. 2) notes, even in comparison to other fields of design, there has been limited academic discourse around the "idiosyncrasies of the textile design discipline." This scarcity of literature, alongside the need for alternative perspectives to give broader access to WholeGarment technology, has led to a research framework that draws from a range of sources, both within textile design and the broader design field.[20]

In the textile design discipline, two key areas are addressed in literature focused on digital knit technologies. One presents narrative accounts of the evolution of seamless knit technologies alongside associated costs and benefits (Choi & Powell, 2005; Power, 2007; Black, 2012). The second explores methods for accessing the technology's creative capability, largely for application in garment design. Design outcomes in these studies are most often realised through application of established design methods as refinements or adaptations through WholeGarment's automatic software. For example, a few studies demonstrate extended garment shaping through replication of established knitted textile shaping methods within the system's prescribed 2-dimensional flat-pattern garment templates (Yang, 2010; Smith, 2013; Taylor, 2015).

The 3-dimensional form-building capability that this research seeks to explore is not accessible through any known means of refinement or adaptation of pre-programmed software. In this aspect I refer specifically to the form-building defined in Chapter Two, 3-Dimensional Knit Fabrication, whereby the investigation is focused on 3-dimensional form or geometries that use WholeGarment technology's capability to construct perpendicular planes.[21] In addition, this investigation did not seek to explore previously realised knitted forms, nor forms with assigned or suggested functional properties.[22] As such, the positioning of this research resides in a largely ill-defined domain.

The lack of representation within this domain emerges from two key constructs. The first relates to the machinery's technological framing whereby WholeGarment's design, as an industrial garment production tool, is seen to mask the machinery's advanced 3-dimensional fabrication capability. As outlined in Chapter Two and discussed further below, some of the technology's design features and the means by which it is marketed and implemented create a system of use which constrains access to capability. Subsequently, there has been limited application or understanding of the technology's potential as a 3-dimensional fabrication tool. In this aspect, the system of use is considered to encompass the physical hardware representing the mechanical configuration of the technology, its design software, and the tools and human resources required to operate these.

The second construct from which a lack of definition emerges concerns the novelty of WholeGarment's fabrication method. More specifically, the fabrication of perpendicular planes within a seamless form, as addressed in this research, is a capability not found in other forms of mass production such as manual or digital machine knitting. Further, while possible to achieve in hand knitting, perpendicular plane development is a complex technique which is seldom used by an average knitter and is not mass producible due to the time-consuming nature of hand knitting. As such, exploration of this capability is not directed by or grounded in replication of regularly used or known knitted artefacts. Rather, the research sits within a new domain in which concepts around geometries, textual language and visual representation of 3-dimensonal knitted form is limited.

Expanding on these two constructs, the following sections begin with a discussion of WholeGarment's design system. The discussion acknowledges the cultural heritage of the knitwear industry embedded within its software and considers its influence on the ways in which the hardware is engineered to work with a specific set of users in a specific design environment; essentially representative of normative ways of thinking about textile, technology and form.[23] Through this discussion, constraints and opportunities for change are revealed. Significant in this regard, and explained in further detail to follow, are alternative frameworks for practitioner engagement and form-building systems.

WholeGarment Design System

Shima Seiki's technology operates as a bundled solution, whereby the knit machinery is operated solely through knit programs developed on a Shima Seiki CAD system. The most recent release of their CAD system is the SDS®-ONE APEX3: a single system for use across the company's full range of knit technologies. Referred to by Shima Seiki (2019a, para. 1) as an "apparel design system," this software includes modules for textile and garment design, virtual sampling and a CAD apparel-production system.

The package of machinery and design system has been developed in a proprietary format such that attributes and outputs are encoded, interpretable only by other Shima Seiki hardware or software. Unlike CAD systems for fabrication technologies such as 3-dimensional printing and CNC machining, there is no interoperability with other software or hardware systems, nor any plug-ins to allow such communication or translation to more commonly accessed design programs. This combination of the technology's proprietary format and a distinct fabrication process results in a specialised knit environment in which both domain and technology-specific knowledge are required for effective engagement and output.

Alongside this, embedded within the design system are a number of elements that derive from both historical practices of and intended application in the knitwear manufacturing environment. Discussed in further detail to follow, these elements, such as distinct designer and technician entry points and an automated design process for templated garment silhouettes, are seen to constrain practitioners in their ability to engage with WholeGarment's advanced fabrication capability.

Software Development and Technical Heritage

Thrift (2005) notes that while software development is often described as a technical process, it is above all a human process in which theoretical and cultural backgrounds influence software design. Feng and Feenberg (2008, p. 115) describe the influence of such theoretical and cultural backgrounds as *technical heritage*, encompassing the "practices, assumptions, and ways of viewing the world" that a community inherits from its predecessors.

While the proprietary format of the WholeGarment design system does not allow for further development of its software, this research does seek to offer an alternative system of use or, more specifically, frame an alternative engagement or way of thinking such that the technology is re-oriented away from its industrial knitwear setting into a broader domain as a textile fabrication tool.

In this aspect the study acknowledges Feng and Feenberg's (2008) instrumentalisation theory and the notion of secondary instrumentalisations, whereby the circumstances around the use of a technology afford an opportunity for it to be reorganised or reimagined under an alternative cultural backdrop.

The premise of this theory, referenced in Figure 3.1, is that relatively neutral and elementary technical elements are combined under a technical code to form strongly biased and contextualised concrete devices. The technical code referenced here derives from the concept of technical heritage, in that it is a type of social standard – a way of understanding specific devices, often reflecting established social practices.

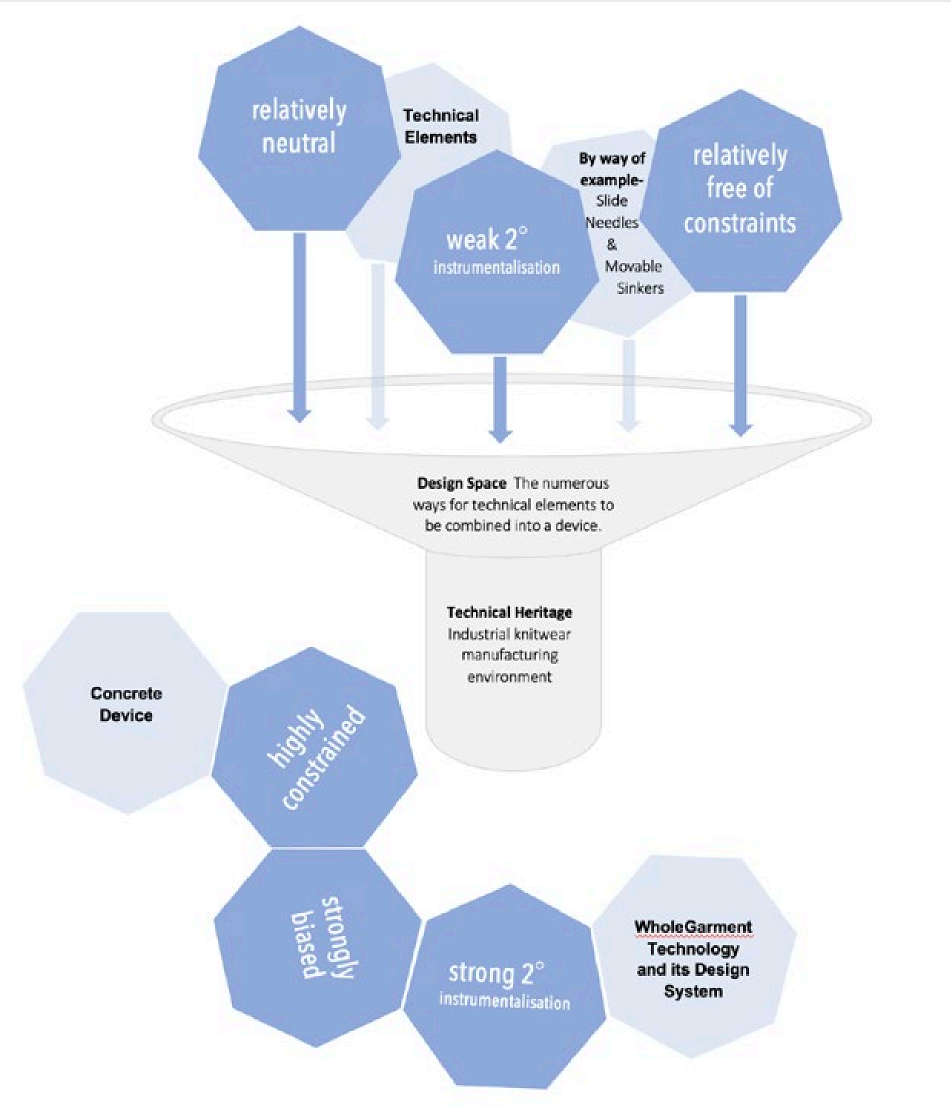


Figure 3.1

Interpretation of Feng and Feenberg's (2008) Instrumentalisation theory, from technical elements to concrete devices.

In the design of WholeGarment knit technology we see that among its technical elements are numerous specialised, distinctive and patented mechanical parts such as SlideNeedles and movable sinkers; parts that give the technology its unique fabrication properties and advanced capabilities (Black, 2012). While primary instrumentalisation concerns decontextualising these technical elements in such a way that we can identify the attributes through which they are assigned function, secondary instrumentalisation is representative of the way in which socially accepted constructs are activated in the organisation of these relatively neutral elements into a technology. In the case of WholeGarment machinery, such socially accepted constructs derive from knitwear production in an industrial manufacturing setting.

There are many aspects of WholeGarment technology's design that are seen to offer a degree of familiarity with regard to the design and manufacture of knitted garments and, as such, may have supported the technology's integration into existing industry settings. However, even within knitwear manufacture, it has proven difficult for knit practitioners to engage with the technology's design system. Application beyond the abstracted garment interface or normative design practice is limited by aspects such as implied division in design and technician roles, and 2-dimensionally derived garment templates constraining creative application and essentially impeding innovative outcome (Brownbridge, 2012; Eckert & Stacey, 1994).

Feng and Feenberg (2008, p. 117) write, "all too often design demands, implicitly or explicitly, that new devices fit with established ways of being," but also acknowledge potential disconnects between intended design and reality, explaining, "even after the release of a new device to the public, it is still subject to further secondary instrumentalizations through user initiative and regulation" (2008, p. 114). In the WholeGarment environment, Underwood's (2009) Shape Lexicon provides an example of a further secondary instrumentalisation in its fabrication of non-garment forms for application in architecture as fibre-reinforced composite structures.

This notion of further secondary instrumentalisation underpins this research and it is from defining this disconnect and the subsequent re-imagining of WholeGarment technology's technical code that the contextual constructs for the research emerge. To explain further, while unable to redesign or modify the software of WholeGarment's design system, the research is grounded in the knowledge that there is extensive accessible capability when the technology is abstracted from its industrial knitwear setting and from the implied processes and outputs of its design system.

The WholeGarment design system is outlined in the following sections. Elements of the knitwear industry's technical code embedded within the software, and which consequently frame its current system of use, are detailed, before opportunities for alternative positionings are discussed.

WholeGarment Design and Production

For the production of seamless garments, the design system is arranged around two distinct user profiles. Though not defined as such, it is evident that these profiles are derived from historical roles within the industrial knitwear setting; that of the knit technician and that of the knitwear designer. Historically, knit technicians worked primarily on the factory floor, engaging with knitted-textile machinery in the industrial production of garments. In this respect, technicians have generally been responsible for construction of knitted forms, including programming of designs and the physical set-up and running of the machinery. In contrast, the role of the designer has been to propose the texture, shape and application of the textile (Volpi, 2014).

Automatic Software

Within the Wholegarment design system there are two distinct entry points to support each of these profiles.[24] The first entry point is through 'automatic software,' which operates in a similar format to a software wizard or set-up assistant. Through this step-by-step process users are guided through the design of seamless knitted garments. The design process begins by selection of a garment template from a small range of pre-programmed silhouettes, before advancing through a limited series of adaptations to the front, back and sleeves of the selected garment. Illustrated in Figure 3.2, this process ends with a *compressed* program for the 'designed' garment within a programming screen. The compressed program is then progressed through an automated series of checks to generate a *developed* program and, lastly, an encoded knit file (000 file), which contains the fabrication instructions for the knitting machine.

In the automatic software process, the design of a garment is highly abstracted from its programming elements or fabrication. Silhouettes based on traditional 2-dimensional, 'cut-and-sew' patterns are presented as flat patterns with a front and back, essentially masking construction techniques and consequently the 3-dimensional fabrication capability of the technology. Further, though the automatic software is established on the parametric constraints of knitted form-building, these are largely hidden from the garment design process. Garment setup and design adaptations are illustrated through simplified 2-dimensional drawings. Any deviation from these is made through engagement with the compressed or developed programs, requiring both programming skill and understanding of construction techniques.

However, there are limited channels in the industrial setting through which designers can acquire this technical literacy and understanding. As Eckert (1999, p. 33) notes, “The specialised nature of this software, expensive licensing restrictions and limited learning resources make it difficult for designers to attain the experience and knowledge required to effectively use the design interface.” Further, cultural barriers to transitioning the traditional knit designer to a more technically empowered role are not just embedded in the technology but continue to exist in industry (Huffa, 2018).

Also relevant to the design of software for manufacturing technologies is that “The impetus for developments in the majority of CAD software is to increase the speed and reduce the risk at which a single operator or team can perform a series of actions” (Masterton, 2007, para. 2). In this context, the automatic software for WholeGarment design is seen to provide an effective solution for the design and fabrication of a small range of garment templates. Complex and unfamiliar fabrication techniques and their associated design principles are largely concealed, minimising program development time and significantly reducing the degree of error within the process. However, as a consequence of this simplification, the fabricated output has also been simplified, with knit designers finding it difficult to realise or influence design outcomes (Power, 2007).

Programming Interface

The alternative entry point, intended for technicians, begins in the same module but bypasses the automatic software process to work directly within the programming interface of the software (Figure 3.3). This interface is essentially a blank 2-dimensional grid. Within the grid, diagrams or patterns composed of coloured squares are assigned functionality as an encoded knit program through the application of a prescribed framework of *option lines.* As a fixed structure of programmable columns (coloured vertical lines) on either side of a diagram, these lines allow for a composition of coloured squares to be read as a knit program.

The 2-dimensional programming grid is a direct translation of the technology’s construction space, whereby each column in the grid represents a needle on the machine’s parallel knitting beds, and each row in the grid is a traverse of the carriage, often a ‘course’ of knitted stitches. The mechanics of the fabrication are such that the carriage can only move left to right and vice versa in an iterative sequence. The first traverse of the carriage appears at the bottom of the program, and fabrication progresses by moving up the program.

Each block of colour applied within the grid represents either a stitch type (e.g., plain, tuck, miss) or a stitch move (e.g., transfer stitch one needle to the left) and the knit bed it should be applied to. That is, whether the stich or move should be

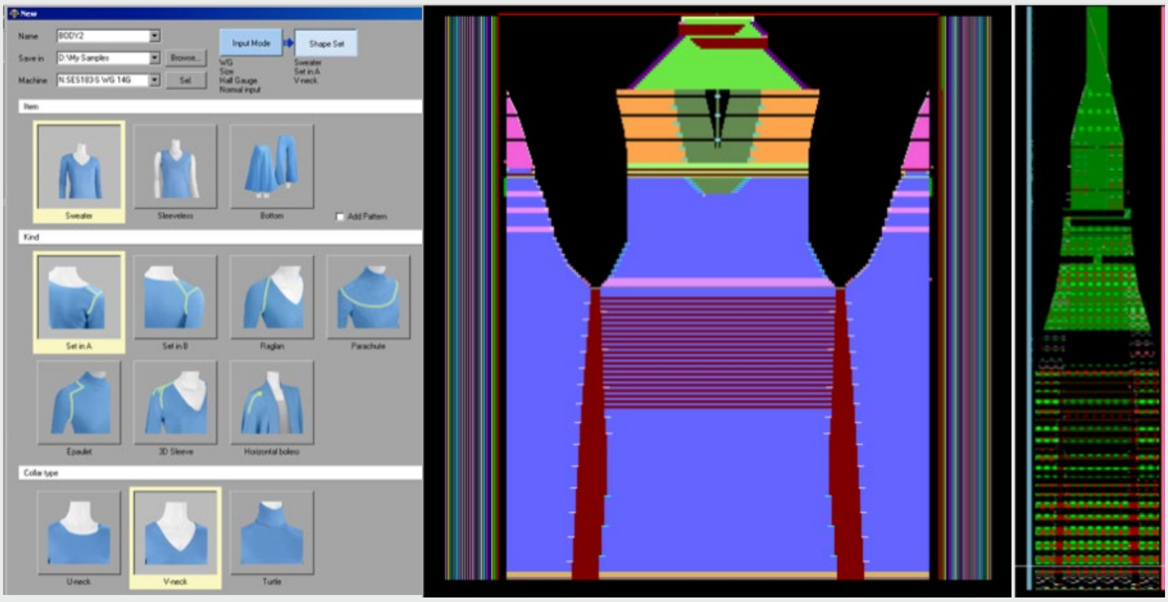


Figure 3.2

WholeGarment design system interfaces, from left to right, garment set-up assistant, compressed program, developed program.

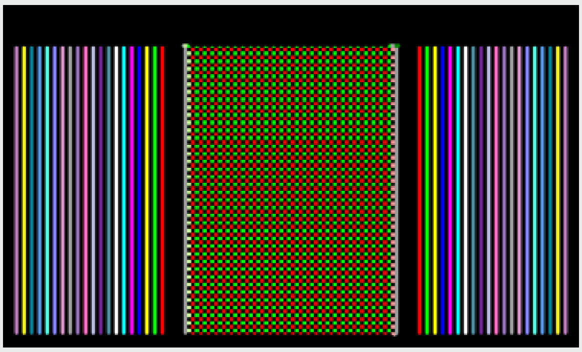


Figure 3.3

WholeGarment programming grid showing tubular knitting, 2018.

Option lines are shown as vertical columns to the left and right of the grid. Within the grid, red squares represent a front-bed stitch and green a back-bed stitch. The blank squares between stitches represent the empty needle of half gauge construction.

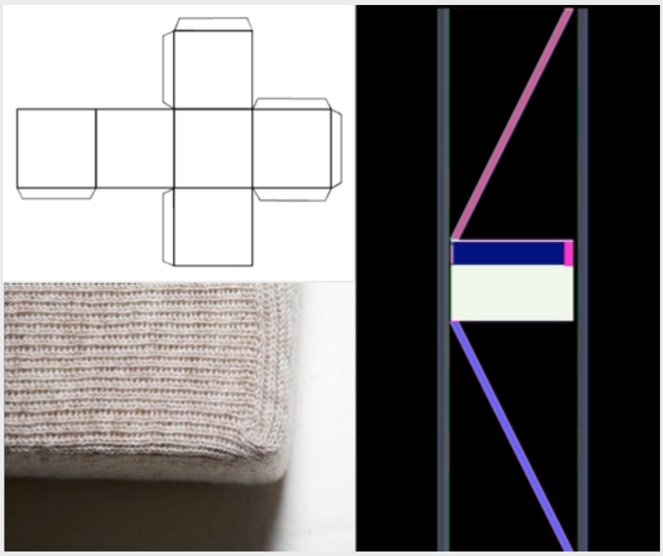


Figure 3.4

Representations of a cube. The image top left is an example of a flat pattern for cube construction. The image on the right shows a compressed program as a 2-dimensional programming grid for a 3-dimensionally fabricated cube, shown bottom left.

applied to the stitch on the front bed, back bed or both. The placement of each block indicates where that stitch or move should be activated such that blocks of colour are placed at the intersection of a specific needle (column) and traverse of the carriage (row).

The option lines (columns) to the left and right of the programming grid allow for additional parameters to be applied to each traverse, such as how much tension or speed to apply to a course of knitting, or which yarn carrier to activate. In this context, the seemingly abstract blocks of colour that comprise a knit program are a visual programming language, with each encoded block encompassing design or construction parameters.

Though the format of the 2-dimensional programming grid has a similarity to the needle and course notation of hand-knit patterns or manually programmed machine-knit punch cards, the encoded squares of colour represent an unfamiliar mode of programming. When combined with the numerous variables that can be applied within the option lines, this unfamiliar fabrication technique leads to a programming environment that can be difficult to grasp, even for experienced practitioners.

However, while engagement requires a high level of programming expertise and a deep understanding of the technology's fabrication technique, in this setting, the programming grid is a powerful tool, allowing extensive control of individual stitches and, significantly with regard to this research, the fabrication of innovative 3-dimensional knitted forms.

Need for a 3-Dimensional Programming Interface

Of significance in this research is the design system's lack of representation for 3-dimensional fabrications. Within the automatic software, garment templates essentially represent digitisation of traditional 2-dimensional flat knitwear patterns. Given the parallel needle beds of the technology and its 2-dimensional programming grid, this translation of flat patterns provides a direct and interpretable translation between the 2-dimensional programming grid and fabrication. However, within this setting of a 2-dimensional grid, the technology's 3-dimensional form-building capability is essentially masked.

In addition, there is no 3-dimensional representation of forms programmed within the programming interface. To explain further, outside of the garment templates in the automatic software wizard there is no graphic representation in terms of shape,[25] drape, volume or tactility linking the 2-dimensional programming grid to the 3-dimensional knitted form it represents (Figure 3.4).

A further constraint to an understanding of fabrication is the limited access to or representation of the parametric constraints associated with the WholeGarment fabrication technique. Within the automatic software, the width and length of a garment are linked within menus for changing the size or shape of the silhouette. However, as Underwood (2009) notes, this application of parametric principles is applied in two dimensions only; the software does not allow for a third dimension within these forms.

With no system to visualise or manage the parametric relationships and tensions of a non-garment knitted form, the calculations and translations associated with form building become a complex element of the design process. Consequently, as is demonstrated extensively in Chapter 5, the design and programming of knitted form requires an arduous and often unproductive mental translation requiring numerous iterations of sampling and development.

Recently, there have been significant developments in this area from Carnegie Mellon Textiles Lab (n.d.) in Pittsburgh, USA. While this is an ongoing project, reported outcomes have included a compiler for translating a 3-dimensional mesh or surface into a knit program. The capability to address the distinct nature of WholeGarment's fabrication and its parallel needle beds within a 3-dimensional modelling system is a promising finding and has the potential to significantly change access to the technology's advanced form-building capability.

Design System Constraints and Considerations for Alternative Systems of Use

The separation of design and technician roles within Shima Seiki's design system and the limited range of garment silhouettes or design variables in its automatic software are frequently referenced in regard to the constrained application of WholeGarment technology. With a simplified but restrictive entry point for designers, in comparison to the technically complex but advanced programming interface for expert technicians, the system is noted for deterring exploratory or innovative approaches to knitted textile fabrication (Eckert, Cross, & Johnson, 2000; Innovation in Textiles, 2012; Taylor, 2015)

Presented with its automatic design software and located in its intended environment of industrial knitwear manufacture, WholeGarment machinery presents as a *strongly biased* secondary instrumentalisation in the form of a knitwear fabrication technology. However, detached from its knitwear setting, and presented with its complex but powerful 2-dimensional programming grid, the technology presents as a relatively weak secondary instrumentalisation. Free of prescribed forms and social or cultural practices, the technology offers seemingly limitless potential constrained only by the skill of its user. It is within this weak secondary instrumentalisation, and the freedom of its associated design space, that this research is positioned.

In seeking to access advanced fabrication capability within this unconstrained design space, two key considerations emerge. The first concerns the knitted-textile practitioner and how they can be empowered to engage with the design potential afforded by WholeGarment's 2-dimensional programming grid. The second concerns the lack of a framework to support 3-dimensional form-building and consideration of alternative approaches. As key contextual issues that inform the research approach underpinning this inquiry, both the knitted-textile practitioner and systems of form building are addressed in the following sections.

Knitted-textile Practitioner, Towards Alternative Frameworks of Knowledge

The need for revised roles and improved technical skills within the WholeGarment knit environment is widely acknowledged both by industry and in research. However, there are differing suggestions as to how to approach this and what the alternative roles should be. Suggestions are centred on an amalgamation of traditional roles with titles such as designer-technician, technical designer and designer-interpreter (Smith, 2013; Taylor & Townsend, 2014; Yang, 2010).

With the intention of re-imagining engagement with WholeGarment knit technology and allowing design practitioners increased access to its fabrication capability, this research takes a similar approach. Here the term 'knitted-textile practitioner' is adopted to encompass, among others, the more commonly labelled roles such as knitted-textile designers, textile technicians, textile-design students, technical textile specialists and textile engineers; essentially any such user who has an interest or intention to engage with WholeGarment knit technology.

In this setting the research also acknowledges the extent of capability accessible to all users of the technology. To explain further, while the distinct entry points in the WholeGarment system have been designed in line with pre-determined user profiles and design approaches, they are not controlled or restricted by any permissions as such. Any user of the WholeGarment design system, regardless of profile, can access the full extent of the technology's advanced fabrication capability. As expertise and understanding of WholeGarment fabrication is extended, users may transition between entry points as their needs evolve, supporting a fluidity in practitioner roles and emergent design approaches.

In this context, the positioning of both design and construction within the same design system allows for these elements to be more closely linked. This fluidity in roles is also supported by it being a digital knit technology. While, historically, technical roles in the knit industry required engagement with heavy machinery, in the digital environment the machinery is more easily controlled by its systems and software, allowing access for a broader range of practitioners (Huffa, 2018). As noted in the section Understanding Fabrication to follow, engaging with the construction of designs considerably extends the level of understanding a practitioner can attain and, subsequently, how far their designs can be advanced.

In framing the knitted-textile practitioner, constructs around computational literacy, fabrication knowledge and design fixation are discussed. In combination, these constructs frame an alternative, informed engagement with WholeGarment knit technology, regardless of fabricated form or application. Within such a framing, it is not expected that the ingrained technical skills and cumulative knowledge held by established knit technicians will be matched by most knit practitioners. However, it is considered feasible that practitioners could attain enough programming and construction knowledge in their specific area of application to allow a hands-on approach with Wholegarment technology; one that allows for more extensive experimentation and a greater degree of expression with regard to their design goals.

Computational Flexibility

The complexity of designing knitted forms in the WholeGarment environment stems primarily from a specialist knit-programming language and a distinct fabrication environment, both of which are inextricably linked to each other within Shima Seiki's CAD system. As such, expert use of the technology requires both programming skill and an understanding of construction. The increasing need for technical literacy has been seen across the design domain, with Smith (2011) defining computational use of design software as evolving through three levels.

The first, *literacy*, suggests familiarity, allowing adequate engagement but not a deep enough understanding that the tools could be used to extend established practices (Smith, 2011). This level of use is comparable to the design of seamless garments through WholeGarment's automatic software wizard. By comparison, the second level – computational *fluency* – allows a user the flexibility to build on existing practice, with an ability to evaluate and understand how and why existing tools may not meet desired needs. This level of use is demonstrated by researchers such as Smith (2014), Yang (2010) and Taylor (2015), who have demonstrated engagement with aesthetic expression and garment silhouette within the templates of the software wizard.

While computational fluency would support an exploration of non-garment forms within the WholeGarment system, the lack of process or template in this area of form building suggests the need for a deeper engagement, in such a way that that experimentation is not compromised based on known solutions.

Consequently, in addressing the objectives of this research, it is the third level of computational use that is of interest – computational *flexibility*. This level is said to provide a practitioner an "ability to create the tools that could solve their problems" (Smith, 2011, p. 66). Here Smith (2011) is not just referring to the flexibility to manoeuvre within a specific software, but also the capacity to determine whether a software meets requirements and, if not, the ability to solve this through other software or by combining tools.[26]

Accepting that digital fluency or flexibility would empower knit designers in their engagement with WholeGarment technology, there remains the challenge of how to achieve this within a specialised, proprietary setting and with what balance of skills. As noted previously, within industry and established educational pathways, even when the need for change is acknowledged, there are limited avenues for designers to attain programming skills and knowledge (Eckert, 1999; Huffa, 2018; Challis, Sayer & Wilson, 2006).[27]

As the knitted-textile practitioner for this research, positioned outside of an industry setting, my level of computational literacy derives primarily from two paths. The first, detailed further in Chapter Five, Computational Literacy, is through training at Shima Seiki's facility in Wakayama, Japan. The second results from the research being located within a university textile lab, detached from the commercial constraints or preconceived notions of role or output that would be found in an industrial setting. In this lab environment, having unrestricted access to WholeGarment technology and being able to draw from the expertise of the laboratory's knit technician have provided the opportunity to extend my knowledge through experiential and self-directed learning.

Understanding Fabrication

Underlying the technical literacy required to design or program forms is the need to understand the distinct fabrication technique of the technology. That is, knowledge and understanding of WholeGarment's mechanical processes allows one to access the full potential of the needle-by-needle control offered by the design system's programming grid. As Masterton (2007, para. 32) notes, "It is important for digital makers to know their tools in the same way as any other craftsperson, …forming an in-depth understanding of these tools is necessary in order to manipulate them in ways that are controlled rather than pre-set."

The positive correlation between understanding of machine movements and understanding of possibility is demonstrated throughout this research. As the design practice progressed, the incremental mapping of 3-dimensional geometries to the machine's needle beds, and subsequent resolution of their fabrication, repeatedly extended my perception of possible forms that could be fabricated with WholeGarment technology.

In the WholeGarment environment, application software comprises two components: the SDS®-ONE APEX3 design system[28] through which knit programs are developed, and the Digital Stitch Control System (DSCS) utilised at the knitting machine. It is within the DSCS system that knit files (000) are uploaded and knit variables such as loop lengths, yarn feeds and take-downs are set.[29] Significant in understanding fabrication are the specific settings that can be applied to each needle movement or stitch, and understanding how these can impact on the effectiveness of a knit program.

Extended literacy in the DSCS system essentially moves the knit practitioner towards a level of technical expertise traditionally associated with knit technicians and, in doing so, supports the knit practitioner in a broader and more independent exploration of knit fabrication. As an example, in the areas of widening and narrowing (as used in + swell and taper in Chapter Five, Part 3), an ineffective take-down[30] setting was initially interpreted as a programming error, as the fabricated form was not shaping as intended. Improved understanding of construction settings ensured evaluation of the design outcome was well informed and potential design solutions were not being compromised by a lack of understanding.

Design Fixation

In the commercial knitwear setting, where WholeGarment technology has most commonly been adopted, the significant difference in design process and fabrication technique in comparison to previous technologies raises the notion of design fixation as a constraint to learning and engagement. Crilly (2015) describes design fixation as the way in which a practitioner becomes fixated on a particular concept or function, often as a result of prior knowledge. The prior knowledge Crilly (2015) refers to includes such aspects as domain knowledge, design processes and other people's ideas. In a sense, this fixation could be defined as the 'technical code' of a practitioner. While all individuals will develop such fixations at varying times in their making practices, the negative impact such fixation can have on the acquisition of new skills or in a new environment is among the factors reported to constrain innovative WholeGarment application.

In that design fixation is personal and experiential, a practitioner's level of fixation can be seen to derive from the tacit knowledge and understanding they bring to the study. For experienced knit practitioners, numerous areas of prior knowledge stemming from long-established knit practices could impede thought and hinder engagement when confronted with a new notation or programming language and radically different fabrication methods. For example, in addition to ingrained domain knowledge, fixation in design process may derive from established methods of making that are not obviously translatable in a new system, or fixation from other people's ideas could stem from the perceived constraints as expressed by other practitioners.

In this research, avoiding design fixation was key to the effective exploration of possibility, in an undefined domain. As Sullivan (2009, p. 48) notes, in knowledge creation, "it is productive to explore creative possibilities that are informed by, but not captive to, existing frameworks of knowledge." While not planned as such, my background and engagement with WholeGarment knit technology differs from the technical code and associated design process inherent in the WholeGarment design system, allowing for – or perhaps requiring – alternative insights, perspectives and approaches to knitted form-building.

To explain further, until postgraduate studies, the only mode of knitted textile fabrication I had known was machine knitting of lengths of cloth – briefly with manually operated hand-flat and Dubied machines and then more extensively through digital flatbed fabrication. As such, there was limited possibility of design fixation from prior knowledge in comparison with experienced knit practitioners, and my introduction to WholeGarment technology started from a point of possibility, rather than an attempt, whether explicit or implicit, to transition or translate prior practice and knowledge to a new fabrication environment.

Further, with no requirement to work with garments throughout my studies, I have had no engagement with the templated automatic software of WholeGarment's design system. Instead, the programming interface has become my design space. In this regard, Masterton (2007, para, 8) writes, "The method in which makers are introduced to digital technologies can be seen as an important component in the way they understand and utilise them within their practice."

I was first introduced to the programming interface in the exploration of visual and haptic aesthetic in undergraduate studies and then, with improved programming skill, used this design space during my postgraduate studies to experiment with shaped tubular non-garment forms. In this regard, WholeGarment's digital making space and the programming language through which designs materialise have become intrinsic to my understanding of knitted textile fabrication. As such, I have not experienced design fixation in the same way as more established practitioners may have, allowing a different perspective on knitted form-building and the use of Shima Seiki's design system.

However, on reflection, design fixation in my own research most commonly resulted from Crilly's (2015) notion of prior knowledge in relation to domain knowledge, or more specifically, a lack of domain knowledge, or even reported possibility, around 3-dimensional knitted cubic forms. As the research progressed into unknown possibilities, my intuition and assumptions were challenged and proven incorrect on several occasions, especially with regard to bias-knit planes.[31] It was not until I had acquired a deep understanding of programming and construction of these planes that I was able to conceptualise possibilities beyond what I had already seen fabricated, allowing for forms previously considered unrealisable to be constructed.

3-Dimensional Knitted Form, Beyond Known Precedents

Feng and Feenberg's (2008) notion of neutral technical elements reminds us that before the application of a technical code, as represented by its design system, there are no prescribed attributes, in this case with regard to knitted form deriving from the WholeGarment knit machinery itself. Rather, the technology's primary output, as knitted garments, emerges from its software, designed for application in industrial knitwear production. Significant in the positioning of this research is the vast possibility in knitted form that exists outside of the garment templates and the system's technical code. With an adequate level of computational literacy, the seemingly boundless design space of WholeGarment technology can be accessed through the programming interface.

In this positioning the research seeks to extend Gero's (1990, p.34) "space of potential designs'; essentially inflating the boundaries of what we consider to be possible.[32] In Gero's (1990) model (Figure 3.5) design outcomes are categorised according to three different approaches. Routine design, such as in the utilisation of WholeGarment's automatic software to generate garment designs, emerges from within the frameworks of existing prototypes, or "when all necessary knowledge is available" (Gero, 2000, p. 187). Non-routine designs are considered innovative or creative. Innovative design, like routine design, relies on precedent. However, in contrast to routine design, it uses methods of adaptation, resulting in designs with, "a familiar structure but with a different appearance because of the unfamiliar variables," (Al-Kazzaz & Bridges, 2011, p. 342). Of particular note here, innovative designs impact on design process, in their introduction of new variables, as well as on the design outcome.[33]

In this research, it is the space beyond known precedents that is of most interest. Creative design represents "the emergence of a totally new product by radically changing particular precedents to bring something new into existence" (Al-Kazzaz & Bridges, 2011, p. 342). Differing computational models have been presented over time to frame the different design approaches (Al-Kazzaz & Bridges, 2011; Gero, 2000). While computational support for design began in the 1960s, the possibility of supporting creative design has emerged much more recently. As Masterton notes, though practitioners are "continually engaging with it [technology] in new and diverse ways, there has been little written on how makers might develop methods that seek to counter these dominant determiners of digital aesthetic" (Masterton, 2007, para. 1).

Alternative Approaches to Form Building

In seeking to extend the design space for WholeGarment technology beyond known precedents, this inquiry looked at alternative engagements and frameworks to offer new perspectives. For example, the scoping phase of this research included engagement with non-knit practitioners through interdisciplinary design projects as a means to draw from different perspectives in form-building. Similarly, a self-directed exploration of the pliable, conformable, surfaces of topological forms was conducted as a means to incite a shift in perspective on the surfaces of knitted geometries. While neither of these projects was pursued directly past the scoping study, outlined in Chapter Five, Part 1, each provided valuable insights, both conceptual and technical, and led to an extended understanding of the elements of knitted form.

As the research progressed into the domain of cubic geometries it became evident that a system of form-building was required to support exploratory experimentation. In the WholeGarment environment there are a number of systems for application in garment form,[34] including Shima Seiki's own automatic software interface. In non-garment form, systems are limited to the compiler for 3-dimensional machine knitting referenced in a previous section, Need for a 3-Dimensional Programming Interface – but which was not accessible for this research[35] – and Underwood's (2009) Package Adaptation System. This system, along with two alternatives from outside the textiles field, is outlined in the following sections. Perceived benefits and limitations of these systems as an approach for this inquiry are also discussed.

Package Adaptation System

In Underwood's (2009) Package Adaptation System, the development of additional tools and representations to work alongside WholeGarment's design system supports form-building of cones, domes and tubular forms. The work draws from the parametric thinking[36] incorporated in design software for industrial design and architecture in establishing a system to support modelling of 3-dimensional geometries in the format of WholeGarment's specialist programming language. More specifically, as illustrated in Figure 3.6, the dimensional relationships between knit program and knit form are presented diagrammatically such that geometries are linked to the knit programming language of their construction.

Underwood (2009, p. 85) notes that "understanding the rudimentary principles of parametric design" offers a new way of thinking about knitted form. While parametric design constraints emerge as a significant aspect in the programming of cubic geometries (Chapter Five, Part 2), the package adaptation system was not adopted as a design approach for this inquiry. As for CAD systems, discussed

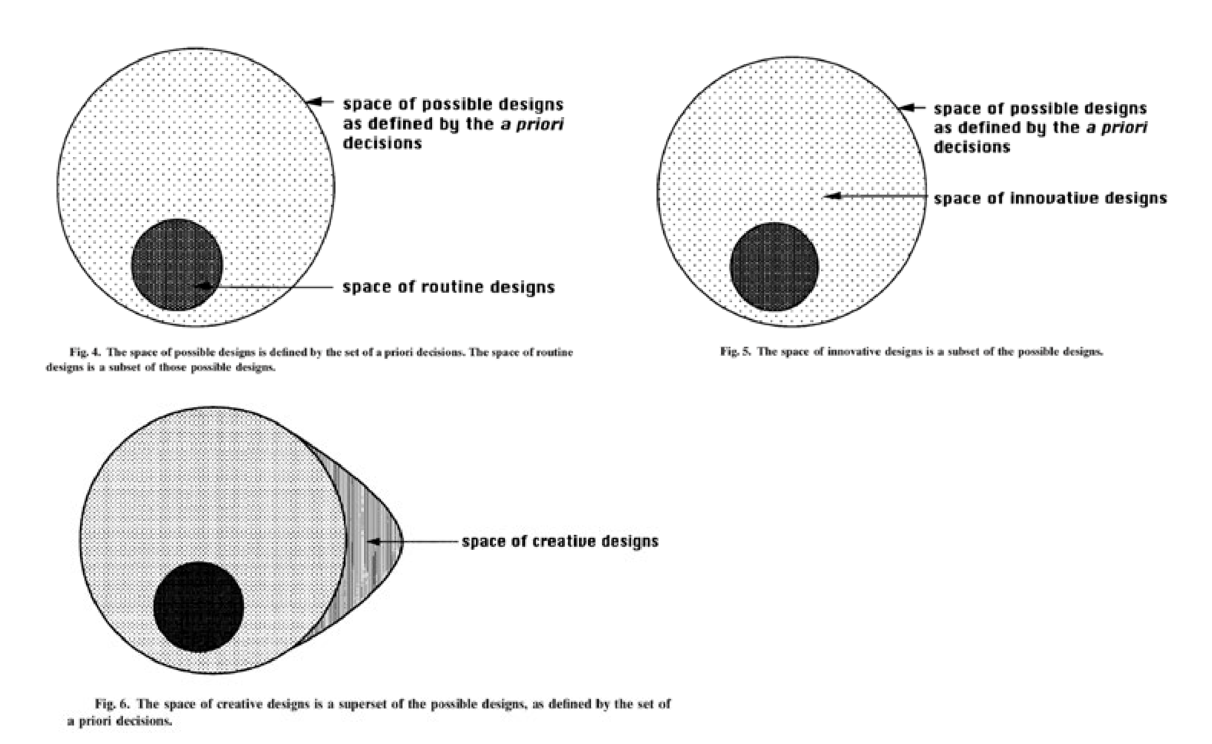


Figure 3.5
Gero's space of potential designs. Adapted from Gero, 2000.

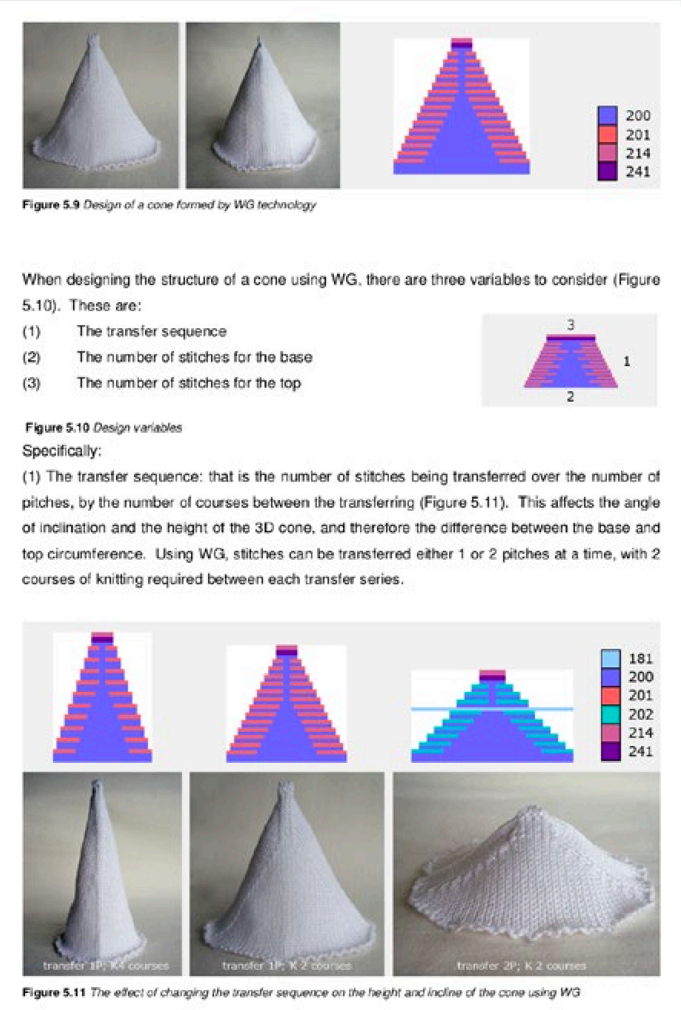


Figure 5.9 *Design of a cone formed by WG technology*

When designing the structure of a cone using WG, there are three variables to consider (Figure 5.10). These are:

(1) The transfer sequence
(2) The number of stitches for the base
(3) The number of stitches for the top

Figure 5.10 *Design variables*

Specifically:

(1) The transfer sequence: that is the number of stitches being transferred over the number of pitches, by the number of courses between the transferring (Figure 5.11). This affects the angle of inclination and the height of the 3D cone, and therefore the difference between the base and top circumference. Using WG, stitches can be transferred either 1 or 2 pitches at a time, with 2 courses of knitting required between each transfer series.

Figure 5.11 *The effect of changing the transfer sequence on the height and incline of the cone using WG*

Figure 3.6
The design of 3D shape-knitted preforms. Underwood, 2009.

in the following section, these provide a method of working with known form-building components. In seeking to radically change precedent in form building, rather than drawing from known components, the research required an approach that supported the surfacing of unknown fabrication capability.

However, as discussed further in Chapter Seven, using the Package Adaption System to represent the parametric constraints of cubic geometries, alongside the findings of this research, would support practitioners in designing with cubic form or its derivatives.

CAD Software

Recognising the lack of 3-dimensional form-building methods in the textiles domain, the research turned to consideration of methods from other domains. As such, CAD software[37] was considered as a tool to support the exploration of knitted forms in this inquiry. This category of software is commonly used for the design of 3-dimensional forms in areas such as architecture, industrial design and engineering. Further, CAD software is often used to produce the program files required for rapid prototyping or additive manufacturing technologies, such as laser cutting and 3D printing. Consequently, the use of such software in the WholeGarment environment, or as an input into the environment, was expected to have numerous benefits, including an ability to visualise 3-dimensional geometry, an accessible and well-resourced learning environment and, given a range of CAD software being widely available, the potential for broader access into 3-dimensional knit form-building.

Despite these potential benefits, after a brief period of exploration it was recognised that the inherent method of form building within CAD software did not offer an easily translatable system for the investigation of knitted forms. Rather, the software presented as a catalogue of components, which could be adapted, amalgamated or manipulated by some means to meet an intended design concept. At this early stage of the research, such a catalogue of components for the WholeGarment environment did not yet exist. Furthermore, the research objectives were focused on establishing a framework for form building. In this regard it was an approach for compiling a set of component forms that was required, rather than beginning with a collated set of geometries from another domain.

Also problematic in the use of CAD systems was that the methods of adaptation or manipulation were not always intuitive or comparable to the particular fabrication method of WholeGarment construction.[38] The ability to model the surface[39] of a geometric form, as opposed to just its mass, suggested an ability to model planes; an aspect that was presumed to be more closely aligned to the 3-dimensional form-building in WholeGarment knit construction than the system's own 2-dimensional programming grid. However, in reality it was difficult to relate the surfaces or volumes of the forms in the software to the 3-dimensional knitted forms that were constructed on parallel needle beds. In addition, some of the terms were confusing when considered in relation to knit construction techniques and, at this early stage in the practice, there was no obvious means of translation.

Operative Design: A Catalogue of Spatial Verbs

The form-building approach chosen for this inquiry emerged in response to the practice. In the scoping phase of the research, Chapter Five, Part 1, the self-directed exploration of the cube as a 3-dimensional knitted geometry was initially approached through self-directed iterations of design cycles prompted by advances in technical literacy. While this phase revealed a small number of cubic form-building components it was constrained by my narrow understanding of fabricated planes, and the lack of a system to frame the experimentation. As a result, a more systematic approach to cubic form-building was sought.

With a cube as a proven geometry, further phases of the research were informed by Di Mari and Yoo's (2018) text, *Operative Design: A Catalogue of Spatial Verbs.* As a text intended for forms and spaces in an architectural field, the system presented was not directly translatable for the knit fabrication domain. However, several elements of its form-building system offered potential as an approach for this inquiry. Detailed further in Chapter Five, Part 2, Considering an Alternative Form-building Method, *these* included the use of performative operatives, or spatial actions, to generate forms as opposed to known components and a representation of the surface of geometric volumes. Further, the format of the text includes multiple modes of representation for each operative – an aspect that emerged as a key principle of the form-building system established in this research. The ways in which this Yoo's text informed the design practice in both its research approach and in its template as a form-building system are further documented in Chapter Four and Chapter Five, Parts 2 and 3.

Language of 3-Dimensional Knitted Form

In exploring the fabrication of 3-dimensional knitted forms the research recognised a lack of framework or language for discussing 3-dimensional knitted textiles. Historically, knitted textiles were flat 2-dimensional surfaces that, through various means of manipulation and assembly, could be shaped into 3-dimensional forms, most often related to the body.

Even in this historic setting, communication is known to be problematic, with Eckert (1997, p. 65) noting the intrinsic difficulty in communicating knitwear information. “The existing symbolic descriptions are either incomplete or very complicated to use. Verbal descriptions are patchy and prone to different interpretations. Knitwear is difficult to sketch.” Taylor (2015) provides a review of various knit languages and notations in common use in her research into craft approaches for application in seamless knitwear. Though the physical formation of different knit stitches does not vary across technologies, differences in notation between technologies or across practitioner roles is common.

In the construction of 3-dimensional forms, elements such as planes, corners or elbows, common to CAD programs, do not exist in knit software or domain terminology. As Underwood (2009) notes, “for designers to be able to engage in authentic 3D shape generation, …the development of a way to effectively communicate 3D form that is not too technical or industry specific is essential.” This need to develop a framework to better navigate and articulate both form and surface of 3-dimensional knitted fabrications is addressed further in Chapters Five, Part 2, Emergence of a Cubic Form-building System and Chapter Six, alongside a discussion of the textual and visual representation of 3-dimensional cubic geometries that evolved through this research.

Summary

In this chapter the current system of use for WholeGarment technology is outlined, with regard to both the influence of the cultural heritage embedded in its design system, and to the opportunities this reveals for alternative engagement, or further secondary instrumentalisation. In the research objective to investigate latent 3-dimensional form-building capability, the notion of a computationally flexible knitted-textile practitioner and non-garment form-building systems are presented as contextual framings to provoke the necessary shift from established practices of making into 3-dimensional form-building, beyond known precedents.

In framing these contextual constructs, the principles from which the design practice has drawn are made explicit. In the following chapter the methodological constructs of the research are outlined. Then the thesis moves on to to a detailed documentation of the design practice as I sought new understandings and knowledge for conceptualising knitted form in a 3-dimensional fabrication environment.

20 In addition to academic literature, feedback and insight was also gained from international conferences and visits to academic institutes and textile research centres. In addition, projects conducted during the scoping phase of the study served to reinforce documented concepts around the constraints and potential in application of knitted forms, while also highlighting elements of concern in the intended re-orientation of WholeGarment technology.

21 While Underwood (2009) provides a methodology for process and representation of form utilising design parameters and Package Adaptations, applied primarily in shaped tubular forms, this does not cover parameters for forms knitted with perpendicular planes.

22 The forms are not completely void of function in that they are intended to demonstrate capability and potential. However, there is not an intended application or purpose past this demonstration.

23 Evaluation of WholeGarment's design system is not made with the intention to replace or substitute existing practices. In this aspect the research is grounded in the belief that the WholeGarment system can be optimised in numerous ways. For example, current methods of engagement with the technology have proven effective in the onshore manufacture of standardised garment forms. This research does not challenge the use of WholeGarment technology in this context. Alongside this, it seeks alternate methods for accessing the technology's latent capability to fabricate 3-dimensional non-garment knit forms, while operating within the parameters of the technology's existing format.

24 The profiling of these entry points and their associated design processes are reinforced by the format of training offered at the Shima Seiki training facility in Wakayama, Japan, whereby technicians and designers are separated, and teaching is focused on different elements of the knit design and construction processes.

25 In recent updates to Shima Seiki's SDS®-ONE APEX3 design system, the areas of virtual sampling and visualisation have been significantly improved. However, this capability is limited to mapping of texture or drape onto garment templates. Changes to the templates are limited and remain with the area of knitted garments.

26 In addition to the technology-specific programming expertise, and with consideration for the notion of computational flexibility allowing a user to see what other solutions may be available, the experimental practice has been supported by other tools such as GitHub for documentation and version control (see Chapter Four, Documentation), and graphic design tools for creating resources to communicate the technology's capability to a wider range of practitioners (Chapter Six).

27 It is encouraging that Shima Seiki have recently updated and expanded tutorials within the help menu of their design system, including a broader range of 3-dimensional graphic simulations showing the needle and carriage movements corresponding to a knit program. This in turn allows another avenue for understanding fabrication technique. Further, is a move to redefine pathways within education. In New Zealand, at Auckland University of Technology, digital knit technologies are introduced in the first year of a Bachelor of Design, Textile Design degree rather than as an area of specialisation later in the degree, and recent graduates have been able to move into industry in roles spanning the traditional designer and technician structures. The Technology Integrated Knit Design master's degree at Nottingham Trent University provides another example. Established to meet the evolving needs of the technology-driven knitwear industry, the course accepts students from both design and technology backgrounds, with the intention of supporting transition into both industrial knitwear production and technical textile industries.

28 The SDS®-ONE APEX3 design system has been outlined in WholeGarment Design and Production earlier in this chapter.

29 The DSCS system contains a high degree of programmable functionality in relation to a range of knit variables such as positioning on the needle bed and repeats for sections of knitting. With advances in the Apex design system, many of these variables can be included in the knit program, and the need to program at the machine is reduced. However, aspects such as stitch lengths and take-down settings can only be programmed at the machine. For further explanation of the operation of DSCS see Mowbray, 2004, and Choi and Powell, 2005.

30 A mechanism to move the fabricated cloth away from the construction area by applying tension to the cloth.

31 For example, with limited understanding of bias-knit planes my perspective of cubic geometries was limited to the application of such planes in one direction only. The discovery of knitting these planes in differing directions, outlined in Chapter Five, A New Perspective on the Knitted Cube, significantly expanded my view of possibility in cubic derivatives.

32 In this, the research does not seek to define all possibility but acknowledges that the probable or proven capability of WholeGarment technology is remarkably small in comparison to perceived potential. This research seeks to define a small area of this potential, focused on 3-dimensional geometries, and in doing so broadens the *space of potential designs*.

33 By way of example, Smith's (2013) use of wedge packages to impart directional changes in existing garment templates results in the presentation of new design approaches for knitted garment design. See Chapter Two, Garment Forms for further detail of this study.

34 For example, the studies presented in Chapter Two, Garment Forms all suggest systems of form-building for garment design.

35 This system is part of an ongoing research project at Carnegie Mellon Textiles Lab, and not accessible for general use.

36 Parametric design is a method of linking dimensions and variables to geometry in such a way that when the values change, the component (shape) changes as well (Underwood, 2018 p. 214).

37 Computer-aided design, or CAD, software refers to a type of program used to create 2-dimensional and 3-dimensional models of physical components.

38 This is not to say CAD technologies would not be beneficial in 3-dimensional form-building. For example, they have potential as a testing mechanism, whereby geometries could be mapped in a way that tested fabrication before being programmed, or as a first step to developing a program. In using CAD software in this way, the unwrapping of the surfaces could provide a programming template. However, this mapping concept in knitted form-building emerged later in the practice and, as such, the use of CAD technologies in this way was not investigated as part of this research.

Chapter Four

Research Approach

Conceptual constructs related to an alternative engagement with WholeGarment knit technology were outlined in Chapter Three, providing a contextual framing for the research inquiry. Emerging from this discussion, and outlined in this chapter, are the practice framework and specific approaches adopted for the study.

The design inquiry in this study is underpinned by the notion of possibility in 3-dimensional knitted form-building; a notion positioned within unknown parameters and ill-defined processes within a largely unexplored fabrication domain. In this regard, Cross (2006, p. 32) refers to design research as a "partial map of unknown territory," while Sullivan (2009, p. 48) notes that "imaginative leaps are made into what we don't know as this can lead to critical insights that can change what we do know." In addressing such design problems, processes of experimental and emergent design, reflective practice, and types of knowing form a framework to support design-led discovery, whereby practices of making, or in this instance, fabrication of knitted forms, provide a means through which the research unfolds.

This chapter discusses the research approach adopted for this study – a study defined by its exploratory investigation of an undefined knitted form-building domain. An alternative methodology comprising of a cubic form-building system for the design and construction of 3-dimensional knitted geometries emerged from this study, and is presented in Chapter Six as a key finding of this research. The approach adopted for this study started from a position of questioning, while the methodology developed through the research and presented in the findings utilised the outcomes of this questioning to establish a component library as its starting point.[40]

While the first part of this chapter addresses the broader methodological framing of the project, the second part outlines key design methods and processes. As the research shifted into a sphere of digital making within an undefined domain, the choice of methods utilised in the design practice transitioned from an emphasis on the self-directed and intuitive crafts-based, hands-on approach that I am most accustomed to,[41] to a focus on computational fluency and articulations of 3-dimensional form informed by form building from other domains. Subsequently, alternative methods for documenting and sharing the practice and its findings emerged.

Methodological Framing

While literature on textile-design methodology, and more specifically knitted-textile methodologies are lacking (Studd, 2002; Glazzard, 2012; Bye 2010), this research is characterised by its reliance on practice as a means of generating new knowledge. In this aspect, new knowledge is centred on alternative engagement and innovative application of WholeGarment technology, and as such concerns both design process and design outcomes. The generation of knowledge through practice is a common attribute of research across a range of design fields and as such the framework established here draws from the broader discourse of the discipline of design.

Flexible and Emergent

Constructs of emergence and non-linearity are commonly attributed to practice-led or discovery-led research. For example, Cross (2006, p. 32) notes "the directions that are taken during the exploration of the design territory are influenced by what is learned along the way, and by the partial glimpses of what might lie ahead." While Rosenberg (2000, para. 33) notes that originality, or creativity, stems from "non-linear links, which destabilizes, makes leaps and seeks alternative paths to those that may be predicted," and that "It leaps between different points in response to irregular and evolving rules."

While this research was primarily advanced through experimental practice, it was informed throughout by a recursive engagement with an emergent and responsive contextual review, personal reflections, and visual and textual analysis. In this sense, design research is opportunistic, making it difficult to determine the research practice in advance. Various models and analogies of design research have endeavoured to capture the attributes of practice-led research. Though, as Boess (2009, p. 4537) notes, "Case studies of design practice have shown that design processes are much more serendipitous, associative, iterative and situation-contingent than models tend to suggest."

As illustrated in Figure 5.1, Practice Framework, recursive engagement, described throughout Chapters Five and Six, allowed for technical and conceptual insights to converge in response to findings and, subsequently, are seen to inform unexpected directions of the research. The flexible and emergent nature of the research has been supported in this study by its setting within a research environment and by a level of technical literacy that allowed for an independent use of WholeGarment technology. In contrast to the more common reliance on a knit technician to realise knit designs, independent use of WholeGarment technology has been significant in determining how far the research could be advanced. Without the need for a technician within the design process, the practice could iterate more freely, findings could be extended or, similarly, when the practice stalled or unexpected findings emerged, changes in direction could be made at will. In this sense, technical literacy allowed for emergent and flexible practice within the WholeGarment environment, and it is within this context that the research is grounded.

Experimental, Experiential and Reflective

Sullivan (2009, pp. 47-48) notes that practitioner, creative output and reflective process all hold equally significant roles within design practice, but emphasises that the critical aspect is “the interdependence of these domains and the central role that making plays in the creation of knowledge.” As such, design practice is concerned with method and reflection, not just design output. In this research, new knowledge resulted from the act of form building in the technical insights that were revealed. However, it was the reflective process of synthesising and analysing findings that revealed the most significant findings. As detailed in Chapter Six, conceptual constructs and research objectives were continuously revisited in the organisation of the exhibition, supporting clarity in reflections and, significantly, it was from this process that the framing of the component library and cubic form-building system emerged; elements which also represent key contributions of this research.

Feedback Loops and Critical Reflection

Feedback loops represent the experiential learning that is gained through iterative cycles of design, allowing for this learning to inform future cycles. In the exploration of an ill-defined digital fabrication domain, and through my position as a computationally flexible designer, my design process transitioned into the sphere of computational code. However, in that the research was exploratory, and notions of form were being challenged throughout, the design process remained reliant on the feedback loops and connections to cloth that derived from a direct engagement with its fabrication. That is, in the development of 3-dimensional knitted form, the process is reliant on a cycle of feedback loops between the knitted textile practitioner, knitting machine and knitted form, where one can only be sure of what has been programmed by physically knitting the object. Thrift (2005, p. 243) references this type of exchange between “human” and “machine,” noting that software acts as a “mediary” with the power to transform and translate its inputs, in this case embedded in the production of new forms.

The significance of this feedback, in the translation between the digital and the material, is referenced by Masterton (2007, p. 4) in his exploration of CNC milling. The author adopts a “hands on exploratory approach to digital software and hardware" to "enable the translation of 3D CAD tests into physical materials." He further notes: "This feedback loop is crucial to my research as it allows an investigation of 'virtual' parameter changes within CAD and CAM to be scrutinised by all my senses."

Types of Knowing

Central to critical reflection is the notion of tacit knowledge; a type of knowledge that can be thought of as 'inexpressible subtleties' – the things that one comes to know intuitively through previous experience (Cross, Naughton, & Walker, 1981). Tacit knowledge and intuition, as a type of 'internal intelligence' or experiential knowing (Albers, 2012; Igoe, 2010), are intrinsically embedded within a practitioner's design process.

The subliminal persuasion of these attributes on the decisions and directions of design practice are particularly significant, and potentially constraining, in the context of seeking new knowledge. Dormer, cited in Igoe (2010, p. 2), "warns of the dangers of reliance on tacit knowledge and the importance of questioning it." To question the tacit, he suggests, "requires the ability to begin to objectify, articulate and challenge assumptions." Within the WholeGarment environment this reliance on tacit knowledge is seen to underpin the constrained application of WholeGarment technology as designers transition from established knit-fabrication environments to a new mode of making. Further, at a more personal level are design habits associated with tacit knowledge that limit my thinking with regards to knitted planes and their possibilities; an aspect addressed in Chapter Three, Design Fixation.

As a knitted-textile practitioner with an established practice that utilises the WholeGarment knit system, tacit knowledge and intuition guide my practice. While this study continues to rely on tacit knowledge of the fabrication environment, it is also clear in its objective to disrupt established practice and known paths. Emerging from this motive has been the transition of my design practice into unfamiliar outputs and an undefined domain, alongside a shift into a primarily digital design space.

Within this space, my limited experience in non-garment 3-dimensional form or associated spatial and volumetric attributes, and the lack of an explicit guide or process for exploring this domain, resulted in a significant decline in the degree of influence my tacit knowledge and intuition has had on the exploration. As is demonstrated in numerous occasions throughout the documentation of the design practice in Chapter Five, a lack of knowledge in regard to cubic planes and the composition of knitted geometries led to extensive cycles of trial and error as I endeavoured to develop an understanding of the relationships between parallel needle beds and 3-dimensional forms. Significantly, the need to work through these experimental cycles, and the development of tools to support the non-intuitive design decisions not only supported the transition of my own understanding , but was also critical to the development of process-mapping diagrams and a form-building methodology, discussed in Chapter Six and detailed in the research findings in Appendix A.

Design Methods

The underlying principles of the study, discussed in the previous section, provided a lens through which the research questions were addressed. In the following sections the specific design methods employed throughout the research are discussed. Cross (1999, pp. 5-6) notes, “Design knowledge resides firstly in people…and secondly in its processes: in the tactics and strategies of designing.” In this regard, with the nature of practice-led research being inherently individualistic, the methods of design activity for any given area of study can also be particular to the researcher.

My textile design practice, regardless of production method,[42] has most often been characterised by craft-based, aesthetically focused knit fabrication. Though form building and digital making have featured more recently (Kalyanji, 2013), they have not played as significant a role as they do within the design practice of this current research. In this study, the positioning of myself as a technically literate practitioner, and the extended transition of ‘making’ into a digital domain is reliant on the adoption of new design approaches and methods within my practice.

Programming as a Method for Accessing Form-building Potential

In the WholeGarment knit environment, ‘making’ primarily occurs within a digital space, represented by the programming of knitted objects, whether through automated software or a programming interface. In this regard the surfaces of a knitted artefact materialise from the sequence and activation of carrier, needle and carriage moves embedded in a knit program. As such, programming emerges as a central method for accessing the form-building potential of WholeGarment technology, essentially acting as a vehicle through which knitted textiles can be moulded.

The process of programming within the WholeGarment knit system has been explained in Chapter Three, Wholegarment Design and Production, along with a discussion of the specialised nature of WholeGarment knit technology and issues of access to training and knowledge sharing. Within this constrained environment, my programming skill and knowledge, and hence what I could achieve through self-directed practice, were progressed through two key avenues; the experiential learning that resulted from the reflective design cycles throughout the practice, and through knowledge assimilated from external experts.

In this research, access to expert knowledge stemmed from two sources. Throughout the practice I was able to seek support from the technician at the Textile and Design Laboratory (TDL) at AUT University. While not practiced in the programming and development of 3-dimensional geometries, as an experienced technician with advanced garment-design programming skills and a comprehensive knowledge of the machinery, this support was most beneficial for seeking second opinions or working through stumbling-blocks.

The other source of expert knowledge was from a three-week training period at Shima Seiki's headquarters in Japan. The role this played as a method for advancing technical skill and knowledge is addressed further in Chapter Five, Part 1, Computational Literacy. Of significance is that the level of computational fluency[43] that resulted from this training allowed for a notable increase in knowledge and insight, in comparison to the iterative cycles of self-directed learning in the early phases of the research. Further, this insight revealed openings and opportunities not previously considered, providing a foundation for the subsequent phases of research. However, as a method, the practice of acquiring programming skill is a repetitive and time-intensive process. Silver (cited in Masterton, 2007, para. 25), notes, "The art of coding is essentially a pragmatic activity," adding that "one learns through doing and through this process builds up a body of knowledge that enables more complex tasks to be achieved."

Operative Design as a Form-building System

The lack of systems for, and reference to, form building in the knitted textiles domain has been addressed previously in Chapter Three, Alternative Approaches to Form Building. Also noted in that discussion was that the use of CAD form-building software as a design approach was problematic due to its incongruity with the construction techniques of knitted form and its reliance on existing components from which its form building draws. At an early stage of the research, such components had not been identified for the WholeGarment environment – rather it was the surfacing of components for 3-dimensional knitted form-building in cubic geometries that underpinned the inquiry.

Subsequently, consideration of the principles in *Operative Design: A Catalogue of Spatial Verbs* (Di Mari & Yoo, 2018) informed the form-building approach adopted for this study. This text provides a systematic approach to the generative development of cubic geometries which derive from the actions of spatial operatives. While compiled for use in architecture and spatial design, the cataloguing of spatial verbs alongside illustrative examples was recognised as a transferable approach for the exploration of geometric form-building.[44]

In addition to the operative methodology that guided my own exploration of cubic geometries, continued reflection on the text throughout the research allowed for a deeper engagement with its content as the inquiry advanced; a positioning that became clearer towards the end of the practical research. In particular, the inconsistencies across spatial and textile domains that are documented throughout Chapter Five, Parts 2 and 3 and the resulting considerations[45] have been key in the unpacking of my practice, allowing fabrication principles of the WholeGarment environment to be defined and articulated.

Prototyping as Fabrication of Forms

As previously noted in Chapter Three, Need for a 3-Dimensional Programming Interface, the lack of a mechanism within the WholeGarment system for testing concepts or 3-dimensional visualisation resulted in fabricated artefacts, or prototypes, being the only means through which realisation of intended design could be evaluated. More specifically, as the physical manifestation of program code, the knitted artefact acted as a test of whether intended design outcomes were met and was essential in the iterative feedback loops that advanced the practice.

Additionally, the collection of knitted artefacts that resulted from the investigation of cubic geometries in Chapter Five, Part 3 embodied the new knowledge and technical insights arising from the design practice, demonstrating possibilities within 3-dimensional knit fabrication. The notion of artefacts as a physical representation of knowledge also underpins their role as look and feel prototypes, which “simulate what it would be like to look at and interact with, without necessarily investigating the role it would play in the user’s life and how it would be made to work” (Houde & Hill, 1997, p. 374). Further, in the research motivation to re-orient 3-dimensional knit fabrication within a broader design domain, the artefacts also acted as boundary objects, enabling collaboration through their “function as translation and transformation devices at the disciplinary or professional boundaries between different work communities” (Nicolini, Mengis, & Swan, 2011, p. 13). The role of artefacts as look and feel prototypes and boundary objects is discussed further in Chapter Six, Presentation of Findings.

Drawing as Articulation of 3-Dimensional Form

In self-directed research, design concepts emerge through evaluation and reflection both during and after phases of making. The lack of mechanism for visualising 3-dimensional form within the WholeGarment system, or of an established form of language or notation for representation of form,[46] resulted in a need to develop my own methods for recording design ideas. Throughout the research various means of textual and visual notations have been used for this purpose. In this section, methods related to drawing or illustration are addressed. Other forms of articulation and notations that emerged for this purpose are discussed in Chapter Five, Part 2, Attributes.

For this investigation of 3-dimensional form-building, the drawing of design concepts is linked to the mapping of a 2-dimensional programming grid, or needle beds, to 3-dimensional geometry; a complexity that is frequently raised as a representational constraint to accessing the advanced capability of WholeGarment technology. Through the practice documented in Chapter Five, Parts 2 and 3, a range of methods emerged to address this complexity, including drawing onto a compressed program for scaling of base segments and mapping needle beds onto sketches of 3-dimensional geometries. The first method was reliant on a printed template on which to evaluate and annotate required adjustments. In contrast, the second method allowed for the conceptualisation of a design within the programming screen, providing an illustration and plan of intended geometry within the digital making space (Figure 4.1).

This conceptualisation of form, and mapping of 2-dimensional grid to 3-dimensional geometry, was needed in part to support the programming of forms, which were not yet intuitive to me. As such, an explicit mapping to guide the composition of knit programs was invaluable for allowing momentum in the programming phases of making. In addition, placing the visual reminder immediately next to the programming grid reduced the need to hold complex translations in my head.

As outlined in Chapter Six, these sketches evolved into process diagrams, which are included in Appendix A, Dimensions Unfolding: Manual of 3-Dimensional Knitted Geometries, acting as both a means of understanding the fabrication of cubic geometries, and as a reference tool that practitioners can use to explore their own designs.

Additionally, the drawings evolved to act as a mechanism for testing the feasibility of designs before engaging in the time-consuming task of programming. In this regard, intended geometries could be trialled through mapping, before deciding whether to pursue the making, or programming, phase of the fabrication process. In this regard one of the constraints was the difficulty of altering existing mappings; an activity that was required more frequently as the practice transitioned into more complex geometries.

Figure 4.2 shows a program version as saved in GitHub. Notes and next steps relating to that particular stage of development are recorded alongside a copy of the program so that one can easily return to that point of development as

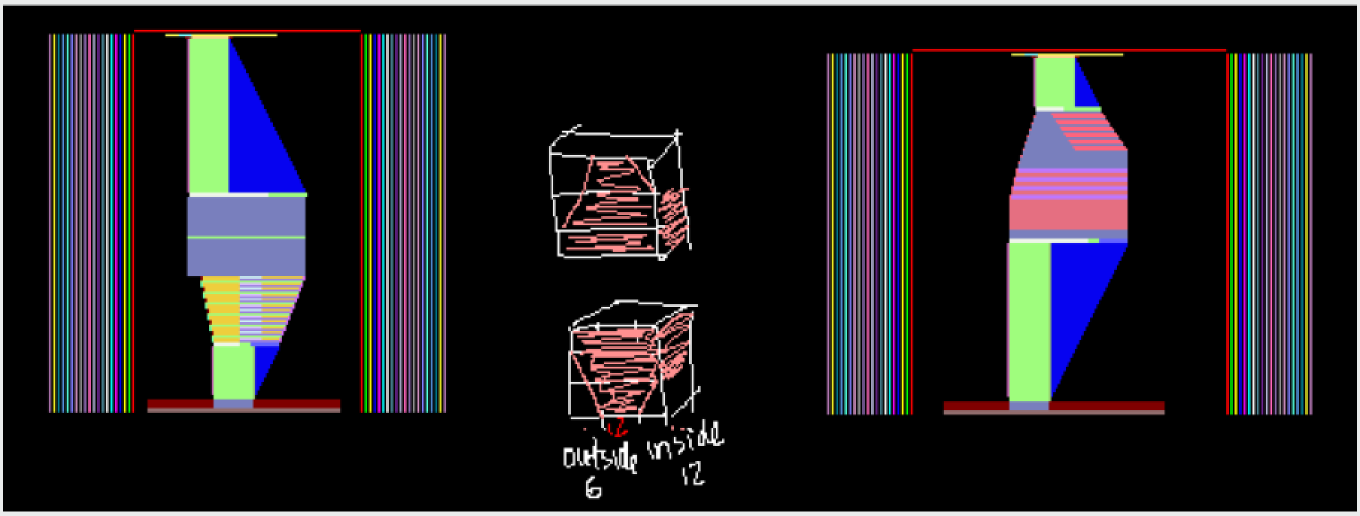


Figure 4.1
Drawing in Shima Seiki Design System, 2018.

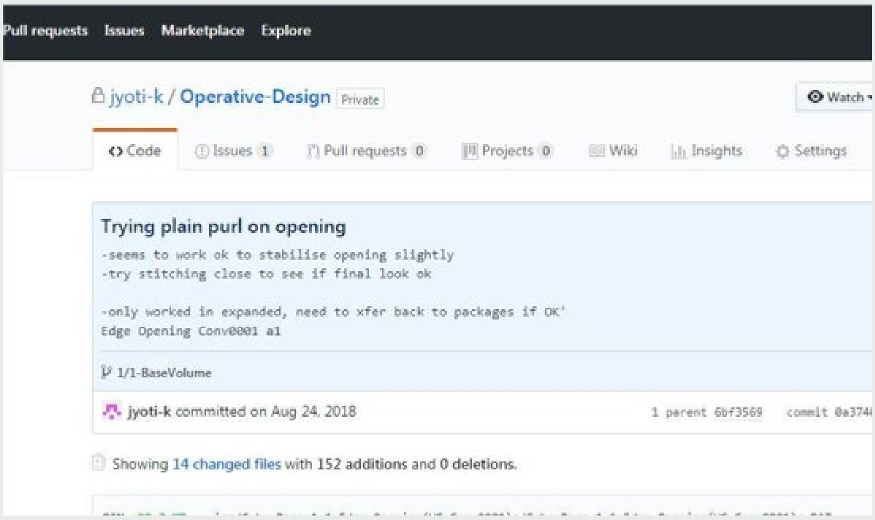


Figure 4.2
Entry in GitHub, 2018

required. As this process was followed continuously throughout the design practice, it also serves to record the research path in relation to thoughts on concept, fabrication and evaluation, and, as such, is a key source of information for the reporting of design practice in Chapter Five.

Unlike CAD tools, the programming interface within the design system doesn't have the ability to layer elements of a composition or easily replicate drawings, therefore iterations or adjustments need to be made by deleting existing aspects of a drawing, or drawing each revision from scratch. As a result, mappings used as a feasibility test in extended geometries are best tested with a prototype at multiple stages in the development.

Documenting the Design Practice

In practice-led research the explicit articulation of design decisions is critical to the validity of the research. As Skains (2018, p. 84) notes, "practice-related researchers push this examination into a more direct and intimate sphere, observing and analysing themselves as they engage in the act of creation." In this research, the physical, hands-on and experiential process within which rapid and variable transitions arise requires tools that can be easily integrated alongside the making process. The following sections outline the primary methods adopted for documenting actions and reflections as the practice moved into a space of digital making.

Research Log

Through all phases of the study a research log, physical or digital, was used to record concepts, process and evaluation. Manual note-taking in journals was most common in early phases of the research as the contextual framing was established and research concepts refined. In later stages of the practice, as programming emerged to be a critical method of designing and making, alternative tools for documentation were required.

Within the Shima Seiki design system it can be difficult to keep track of conceptual considerations and revisions to knit programs, especially within an exploratory design practice where multiple iterations and tests are required to progress form development. Given the abstract nature of the coding language and the levels of detail that changes can be made at, such as modifying a single course or even a single stitch, amendments to knit programs are not always obvious. Further, there is no mechanism within the design system for recording notes or comments as you might be able to do in other CAD/CAM or graphic software. Annotations can be made within the programming screen, but this is limited by the volume of text-based detail that can be recorded and must be done outside of the programming grid.[47]

Previously, tracking program revisions included such methods as making copies of a program and annotating each version, saving multiple copies of the program, or recording changes in a journal against a photograph or screenshot of the program or relevant section of code. However, these methods are restrictive when utilised in iterative testing and development. The time taken to save program versions and the annotating of changes within a different medium is time consuming and disruptive to the flow of the design and programming process; a mentally consuming task in itself due to the continuous dimensional translations being attempted.

In addressing these limitations, the research utilised GitHub – a free, open-source version control system that keeps track of software revisions, with modifications stored in a central repository. As a new method of documentation that allowed for versions and annotations within a digital workspace, this method was invaluable in documenting the practice. Accordingly, its use is outlined here in further detail.

GitHub as an Online Catalogue and Journal

It took some time to understand how to work effectively with Git and GitHub – incorporating their use required me to be systematic in my design and documentation practices in each step of the work. This involved a reflective and iterative process of breaking down my work practices to the specific steps involved, the systems I interacted with, and the various design and program artefacts these generated and changed. Beyond embodying this decomposition of practice, the system is designed to capture a narrative of the work being done, as it is done, hence requiring self-reflective documentation to be created incrementally at each step of the process.

Due to the proprietary nature of Shima Seiki's design system, the 'code' of knit programs cannot be recorded. Common application of version-control software would record changes to coding within each entry. However, while not able to read the code as such, Git software, and specifically access through the GitHub desktop client, is still effective in its ability to store program iterations alongside commentary and reflection, essentially acting as an accessible online journal and cataloguing system that can be used alongside the Shima Seiki design system.

The second area in which version control was advantageous relates to the methodology that emerged[48] for the development of 3-dimensional geometries. Within a largely speculative form-building dimension, derivatives of geometries are continuously branching and evolving, so the desire to return to previous iterations or 'jumping-off points' is a common occurrence. Within a system such as GitHub, the ability to branch allows for a program to be duplicated and adapted without losing the original version. In this way, the origin of the branch and all derivatives are clearly tracked, and one can revisit any version of an original (master) or branch at a later stage.

As WholeGarment knit technology transitions into a broader design domain it is expected that form building may become more complex, and the 3-dimensional knit domain will be further populated. The use of a tool such as Git allows for an easily accessible database of components and compositions so that emergent forms can be developed through building on existing knowledge. Further, as an online tool that accommodates images and annotations, Git facilitates collaborative form-building and distributed teams for more extensive product development.

Annotated Artefacts

In contrast to previous phases of my design practice, the visual aesthetic of the knitted cloth did not play a significant role in this research. More specifically, the aesthetic focus in this research was on the form of knitted-textile fabrication, while the pattern, texture and colour embedded within this fabrication remained consistent throughout. As a result, the volume of sampling, and the degree to which these were documented is also reduced. As referenced previously, evaluation of artefacts more commonly resulted in programming feedback, which was recorded in a journal.

Most often, evaluation and reflection on knitted artefacts was documented through notes attached to the fabricated forms. Though making, or programming, in the WholeGarment environment is primarily a digital process, physical interaction with the fabricated form is critical to progressing the practice, allowing for the evaluation of planes against intended concepts and the mapping of planes to program. In this process of evaluation and reflection, the recording of thoughts attached to the knitted form allowed for immediate response and reaction to be captured with minimal disruption to the thought process. Further, with the design focus on form building, it is these physical forms rather than journaled notes that are most often revisited when seeking to understand or advance practice.

Synthesis and Dissemination

The notion of multiple strands within this research, each unfolding in parallel, has been discussed previously. Each strand responded to advances in both its own development and those in parallel strands as the practice traversed the various conceptual framings and findings of the research. Drawing the various strands of practice and reflection together at two distinct stages was critical for assessing and advancing the research, essentially allowing for the practice to be critiqued as connections and insights were distilled.

In this research there were two key mechanisms through which research synthesis and critique occurred: exhibition and thesis. These can be seen to act as distinct phases within the practice, enabling a mediation between the various strands, and opening the practice up to external engagement. However, the role they played in advancing the research was also significant. As much as these formats gathered forms, strands and knowledge together, it was the insights that developed through this process and the subsequent reflections and reactions that significantly influenced the research findings.

Exhibition

In this research the exhibition served two purposes; the first was as dissemination of research findings as part of the examination process for practice-based PhD research. The second was as a research method; a role that emerged through the acts of curating and installing the exhibition, which demanded and enabled further synthesis and analysis of the research.

Writing about the display of artefacts following creative practice, Nimkulrat (2007, p. 4) notes that the "practitioner-researcher analyzes and contextualizes the resulting artifacts as well as the creative process that went into it" The author further explains that this process of making and exhibiting can continue until the practice yields satisfactory answers to the research questions. Through the course of my research career, exhibition of practice or resulting artefacts has most often occurred at the end of the research period and is viewed primarily as a dissemination of research. With consideration given to Nimkulrat's statement, it became evident that after the completion of that particular course of research, the synthesis and analysis resulting from each of the exhibitions was taken into another course of research. In the case of this PhD research, the positioning of the exhibition before completion of the research text and, subsequently, the synthesis and analysis that resulted both during and after this process, allowed for the research to be advanced to a further level of understanding and insight.

The components within the exhibition, its role as a research method, and the insights revealed are discussed further in Chapter Six, Presentation of Findings.

Thesis

Critical to practice-led design research is the need for the design process to be made explicit. Nimkulrat (2007, p. 6-7) notes that "Documentation renders the implicit artistic experience accessible and discussable in the context of disciplined inquiry." In self-directed practice, one's thought processes, findings and learning often become embedded in the research journey and evolve into intuitive actions before one is able to process or make them explicit. As with the exhibition, the process of compiling this text about the research made connections between thought and practice apparent, or reinforced them, allowing the various threads from different components of the work to be made explicit.

Summary

The methodological framing for this research is grounded in three key interrelated constructs: a flexible and emergent framework, experimental design practice, and types of knowing. Within this framing the research was advanced through processes of making, informed by the spatial operatives of a form-building system. In the WholeGarment environment, these making processes are primarily positioned within a digital space, with programming as a key design tool and supported by digital methods for drawing and documentation. The making element of this research is detailed further in the following chapter.

In contrast to the digital making space, the physical space of a gallery acted as a mechanism for synthesising the various strands of the research, allowing for review and analysis of the tools and geometric forms which emerged from the practice. Through this process, documented in Chapter Six, the research findings are consolidated into distributable artefacts as a form-building manual and photographic catalogue of knitted cubic geometries (Appendices A and B).

39 As in the surfaces of a 3-dimensional form. This design element can be given different names in different software programs. For example, surfaces are named 'NURBS surface' in Rhino 3D and a 'face' in SketchUp.

40 This component library is also an undefined space, in that its initial components result from this research but further investigation of the domain is required to populate it.

41 See Kalyanji (2013) for a discussion on crafts-based making practices.

42 My design practice has developed across a range of production methods, moving from hand flat to v-bed, and on to digital.

43 For a discussion of computational levels of use, see Chapter Three, Computational Flexibility.

44 The text is focused on cubic forms, as are common in architecture. However, as a system of exploration, this could be utilised in series with other base volumes such as cylinders, spheres or cones.

45 For example, the discussion concerning the emergence of alternative operatives in Chapter Five, Part 2, Operatives.

46 The lack of language or framework for 3-dimensional knitted form is discussed in Chapter Three, Language of 3-Dimensional Knitted Form.

47 As the WholeGarment system is a garment-manufacturing tool within the knitwear industry, the need to retain multiple versions of a knit program throughout its development does not appear to be critical. Within this setting, garment programs are commonly developed by knit technicians, often based on programs generated for previously developed designs. As such, there is a reduced degree of experimentation in comparison to the research and development of non-garment forms or more speculative exploration. Further, in the knitwear production environment it is common practice to have just one approved version of a program for each sample or prototype, rather than at various stages along the way.

Chapter Five

Dimensions Unfolding Design Practice

At the core of this research is an exploratory design practice. It is through this practice that the research inquiry has emerged and is addressed (Niedderer, 2007) and as such, it is the mechanism through which new knowledge and understanding unfold. This chapter documents the design practice, detailing the intensive making phases alongside discussions that enabled reflections and insights to be made explicit. As practice-led research, the path of inquiry was responsive to the varying strands of the research and the insights they revealed. As such, this is an extensive chapter, presented in three parts, as outlined below.

Throughout the chapter, technical findings and conceptual insights are detailed as they emerge. Though the technical findings can be complex to digest it has been difficult, and would be detrimental to the research, to separate them from conceptual and theoretical constructs within the documentation. To explain further, the design practice sits within an under-explored area of technological capability. Within this space of digital making, technical elements are intrinsically linked to design concepts; each aspect informs the others through the continuous translations between digital interface and physical form as the practice advances.

As such, documentation of the practice includes reflection on both technical elements and design concepts, as it explains the connections and design decisions made throughout the research. Supporting this documentation, and the reading of this chapter, is the practice framework, Figure 5.1. Within this framework key findings from each phase of the inquiry are identified, allowing the practice-led path of discovery to be made explicit.

The chapter spans three sections, moving from exploratory and instinctive experiments to more systematic and analytical developments. These parts are outlined in the design practice framework, Figure 5.1, and are summarised below.

Part 1 – Preliminary Studies

The design practice was initiated by an exploratory phase whereby three alternative paths were pursued in an attempt to disrupt established form-building practice within the WholeGarment environment. The varying paths looked to external inputs and concepts in the form of interdisciplinary projects, topological surfaces and technical literacy, and acted as scoping studies for the research. While all paths revealed alternative perspectives on knitted form and surfaces, it is the path of computational literacy and the exploration of cubic geometries that was extended into self-directed experimentation. The significant shift in understanding of cubic forms that emerged from this path, and more specifically the fabrication of cubic planes, allowed for some early variables within the form-building domain to be identified, which in turn motivated further investigation.

Part 2 – Foundation for a Form-building System

In this part the research turned to a more systematic investigation of cubic form as it sought to define the domain of 3-dimensional knitted cubic geometries. Informed by Di Mari and Yoo's (2018) text, Operative Design: A Catalogue of Spatial Verbs, the practice investigated the fabrication of a base cube and its segments as templates for cubic derivatives.

Emerging from this phase of making, and in combination with findings in Part 3 and Chapter Six, the elements of a cubic form-building system developed. The system and its components are intended as a framework for the ongoing investigation of 3-dimensional knitted geometries. The multiple modes of representation within the system derived directly from the design practice and, as such, represent key findings from the research, ranging from broadly interpretable design concepts to WholeGarment-specific technical mappings.

Part 3 – Investigation of Knitted Cubic Form-building

As the cubic form-building investigation is continued in Part 3, the feasibility, parameters and constraints of a range of cubic geometries are documented within the framework of the cubic form-building system outlined in Part 2. As the practice advanced, affordances and limitations of WholeGarment capability were revealed, allowing for some definition within the knitted cubic form-building domain. In addition, the fabrication of these geometries led to the development of tools and systems to support form-building practices; elements of the inquiry which are detailed further in Chapter Six, Synthesis of Research Findings.

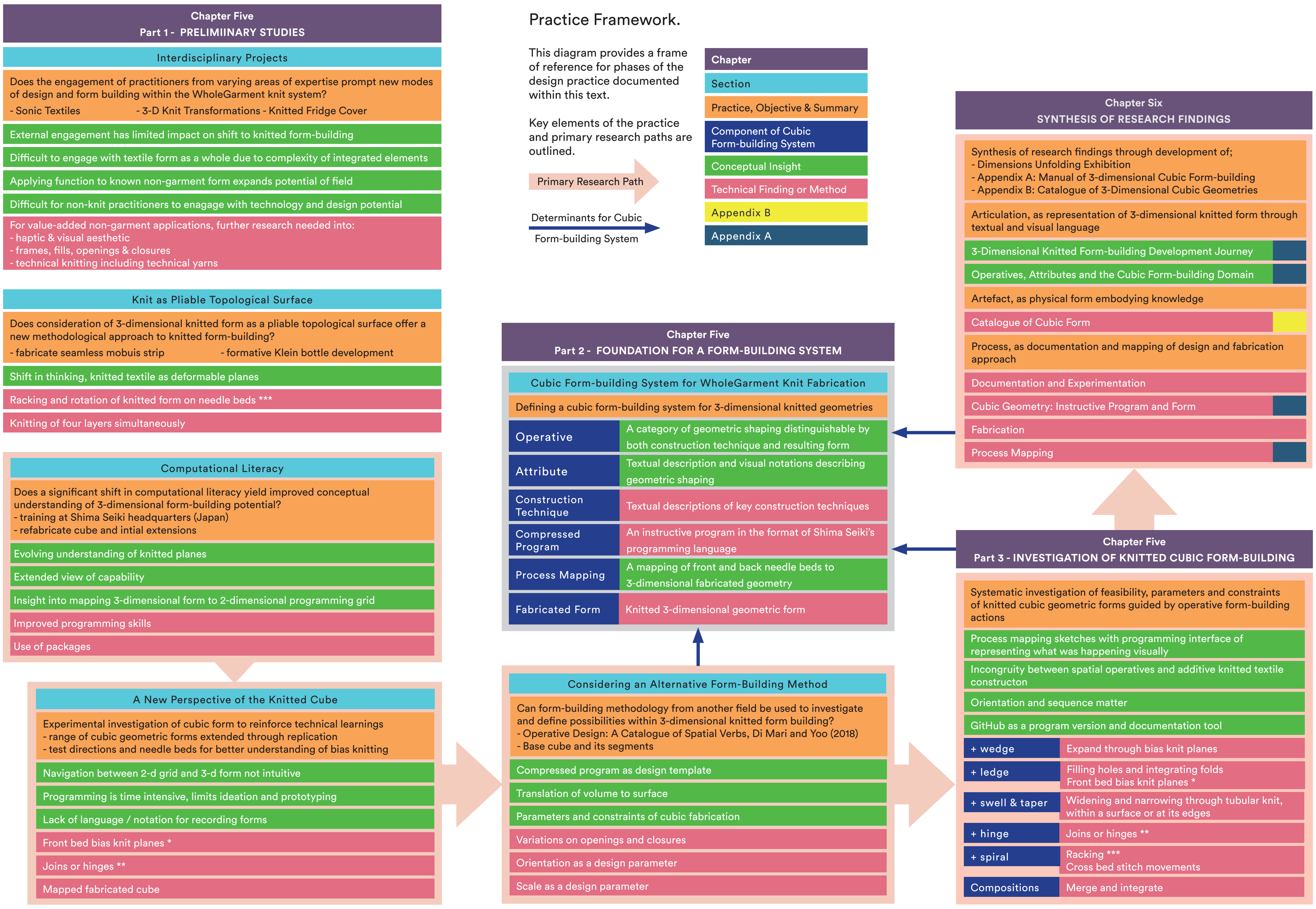


Figure 5.1
Practice framework.

Chapter Five
Part 1 - PRELIMIINARY STUDIES

Interdisciplinary Projects

Does the engagement of practitioners from varying areas of expertise prompt new modes of design and form building within the WholeGarment knit system?
- Sonic Textiles - 3-D Knit Transformations - Knitted Fridge Cover

External engagement has limited impact on shift to knitted form-building

Difficult to engage with textile form as a whole due to complexity of integrated elements

Applying function to known non-garment form expands potential of field

Difficult for non-knit practitioners to enagage with technology and design potential

For value-added non-garment applications, further research needed into:
- haptic & visual aesthetic
- frames, fills, openings & closures
- technical knitting including technical yarns

Knit as Pliable Topological Surface

Does consideration of 3-dimensional knitted form as a pliable topological surface offer a new methodological approach to knitted form-building?
- fabricate seamless mobius strip - formative Klein bottle development

Shift in thinking, knitted textile as deformable planes

Racking and rotation of knitted form on needle beds ***

Knitting of four layers simultaneously

Computational Literacy

Does a significant shift in computational literacy yield improved conceptual understanding of 3-dimensional form-building potential?
- training at Shima Seiki headquarters (Japan)
- refabricate cube and intial extensions

Evolving understanding of knitted planes

Extended view of capability

Insight into mapping 3-dimensional form to 2-dimensional programming grid

Improved programming skills

Use of packages

A New Perspective of the Knitted Cube

Experimental investigation of cubic form to reinforce technical learnings
- range of cubic geometric forms extended through replication
- test directions and needle beds for better understanding of bias knitting

Navigation between 2-d grid and 3-d form not intuitive

Programming is time intensive, limits ideation and prototyping

Lack of language / notation for recording forms

Front bed bias knit planes *

Joins or hinges **

Mapped fabricated cube

Figure 5.2
Practice framework, Part 1.

Part 1

Preliminary Studies

My previous practice has mostly been intuitive and self-directed (Kalyanji, 2013). However, in this initial, exploratory phase of the research, Figure 5.2, I looked to external sources in an attempt to incite a notable shift away from established design concepts and process within the knitted-textiles domain. Three studies were conducted: interdisciplinary projects, topological surfaces and computational literacy. Each was motivated by a different approach, with the expectation that the range of insights revealed would help support the development of a contextual and methodological framework for the research.

The studies, and the technical and conceptual insights they revealed, are outlined below in further detail. As depicted in Figure 5.2, two of the paths, interdisciplinary projects and topographical surfaces, were not pursued directly beyond this first phase. However, insights from these paths informed the contextual framing of the research, sometimes reinforcing findings reported within the literature, and at other times revealing unexpected possibilities. Further, the technical findings, in terms of construction techniques and programming tools, increased the level of domain-specific knowledge I was able to draw from in subsequent phases of the practice.

The path of the third study, computational literacy, was extended beyond the initial format. Recognising that my strengths were grounded in technical knowledge, specifically programming expertise, and that improved understanding of fabrication techniques had offered a new perspective on the possibilities of form building with knitted planes, the research returned to self-directed practice in this and subsequent phases.

Interdisciplinary Projects

Does the engagement of practitioners form varying areas of expertise prompt new modes of design and form building within the WholeGarment knit system?

The intention in this study was to engage with knit and non-knit experts from a range of fields in collaborative or client-directed projects. The expectation was that working with practitioners from varying design backgrounds would provide an avenue for disruption of established form-building practices, or prompt the exploration of 3-dimensional knitted forms not previously considered or realised. In addition, participation in, and observation of, these projects was expected to act as a scoping study for consideration of the access and understanding of non-knit practitioners to the WholeGarment environment, and for early insight into the mechanisms that may allow a shared understanding across discipline boundaries.

Practice

I participated in three projects as a knit technology specialist. In defining myself as a knit technology specialist I am distinguishing my skill base from that of practitioners from other fields, as well as highlighting that I am neither a traditional knitwear designer nor a traditional knit technician. While the interactions across each project differed according to needs, my primary role in all projects was the translation of design concepts into programming and fabrication of the non-garment forms.

Sonic Textiles

Sonic Textiles was a component of a study in e-textiles by a postgraduate researcher with a background in creative technologies.[49] The intention in this component, shown in Figure 5.3, was to integrate electronic functionality into knitted cloth such that the textile form would act as a sensor, responding to stretch and compression to produce varying audio tones.

Figure 5.3

Sensor Squab Cover from Sonic Textiles, Charlotte Alexander, 2015.

A squab cover, as a known form, was chosen for this work. Iterative cycles of development focused on integrating conductive yarn into the form and the relationship between stitch structure and electrical resistance under various tensions. The shape of the form itself was not a focus of the research. Progression was reliant on continuous feedback loops and the sharing of knowledge and ideas, as neither of us was familiar with each other's area of expertise.

The learning from this project primarily related to the integration of electronics within the textile's construction. Most often, knitted e-textiles are seen in flat cloth or in garment forms. This study demonstrated that sensory and tactile qualities can also be embedded within 3-dimensional knitted geometries. In addition, it extended the scope or function of knitted-textile fabrication through applying an alternate functionality to a known geometric form.

3-D Knit Transformations

3-D Knit Transformations was a collaborative project with two additional knit specialists: one an experienced knitwear designer and the other an experienced WholeGarment knit technician.[50] The aim of the project was to develop a collection of 3-dimensional garment and non-garment artefacts through a transformational shaping process. A sleeveless garment with a curved hem and parachute shaping[51] developed by the knitwear designer was chosen as a starting point.

All participants had experience of working with WholeGarment knit technology, which contributed to a shared understanding of the knit environment. However, each had their own areas of specialisation. The project concept was developed to incorporate the individual strengths of each participant relating to form, texture, 3-dimensionality and technical programming. Therefore, iterations between specialists were nested within the iterative design cycles of the broader development as each participant contributed their specialist skills to advance the design of forms.

Attempts to use collaborative software for brainstorming and documentation of the process were unsuccessful. Though participants had a shared understanding of the environment, the lack of a common language, textual or visual, made it difficult to record meaningful commentary. As each participant drew from their specific area of expertise to contribute to the construction of forms, knowledge sharing was most often in person, at stages of handover and evaluation.

The project resulted in a range of forms exhibiting 3-dimensionality and transformation, shown in Figure 5.4. Further, in contrast to the perceived aesthetic constraints of the WholeGarment environment, the forms demonstrate expressive visual and haptic qualities (Smith & Kalyanji, 2014). However, the shape of the forms is still fairly conventional and though methods for framing and filling these forms were adequate for the purposes of the project, they were not well resolved. It was proposed that input from outside of the knitted-textile field could allow for non-knit components to be better integrated.

Of note, though all participants had an expert level of knowledge, the breadth of the field is such that none of the participants could have developed these forms[52] on their own. In this context, as knitted form-building extends into more complex structures, the continuation of knit specialisations appears to be beneficial (Smith & Moore, 2019). However, it is also expected that these specialisations will evolve to address the changing fabrication systems and applications of knitted cloth.

Knitted Fridge Cover

Knitted Fridge Cover was a client-led project in which an industrial designer approached AUT's textile and design lab to develop a knitted sleeve to cover a refrigerator. The project was part of a charity auction, and as such the cover was focused on aesthetic qualities rather than functional attributes. However, the concept was aimed at "keeping the fridge snug as a bug as it cools your food inside"[53] and was printed post-fabrication with an icicle pattern, as shown in Figure 5.5. In this project both the lab's technician and I worked with the industrial designer.

With limited knowledge of the knitted textile environment, the brief provided by the designer was abstract and conceptual, with no indication of the format such a cover would take. Dimensions of the refrigerator were provided, but it was soon realised that the curved dimensions were difficult to assess, especially against a pliable knitted fabric, and consequently the refrigerator was brought into the lab to enable faster testing and a more accurate finish.

Additional aspects such as fastenings were also left to the lab to develop and, given our limited product-design knowledge, were based on techniques commonly used in garments. Openings were integrally knitted into the cover so that brackets and the door handle could be fastened over the top of the cover. Tubular knit along the edges of the cover allowed for elastic to be threaded for fastening the cover to the appliance. A more collaborative approach in this area could have yielded a better-quality finish.

A lack of shared understanding of the fabrication environment appeared to constrain the input of the industrial designer. It appeared the client was uncertain his design concept was even possible and, as such, with a limited time frame, was willing to accept whatever suggestions were made. In this regard, while it was valuable to have an unknown concept driving the development, there was little consideration for alternatives as the knit specialists worked to adapt a known form (squab cover) into a viable solution.

Technical Findings and Conceptual Insights

Each of the interdisciplinary projects involved a different group of participants with differing objectives. As such, the projects provided an opportunity for preliminary observation and insight as to the needs of engaging with practitioners from a range of design fields within the WholeGarment environment.

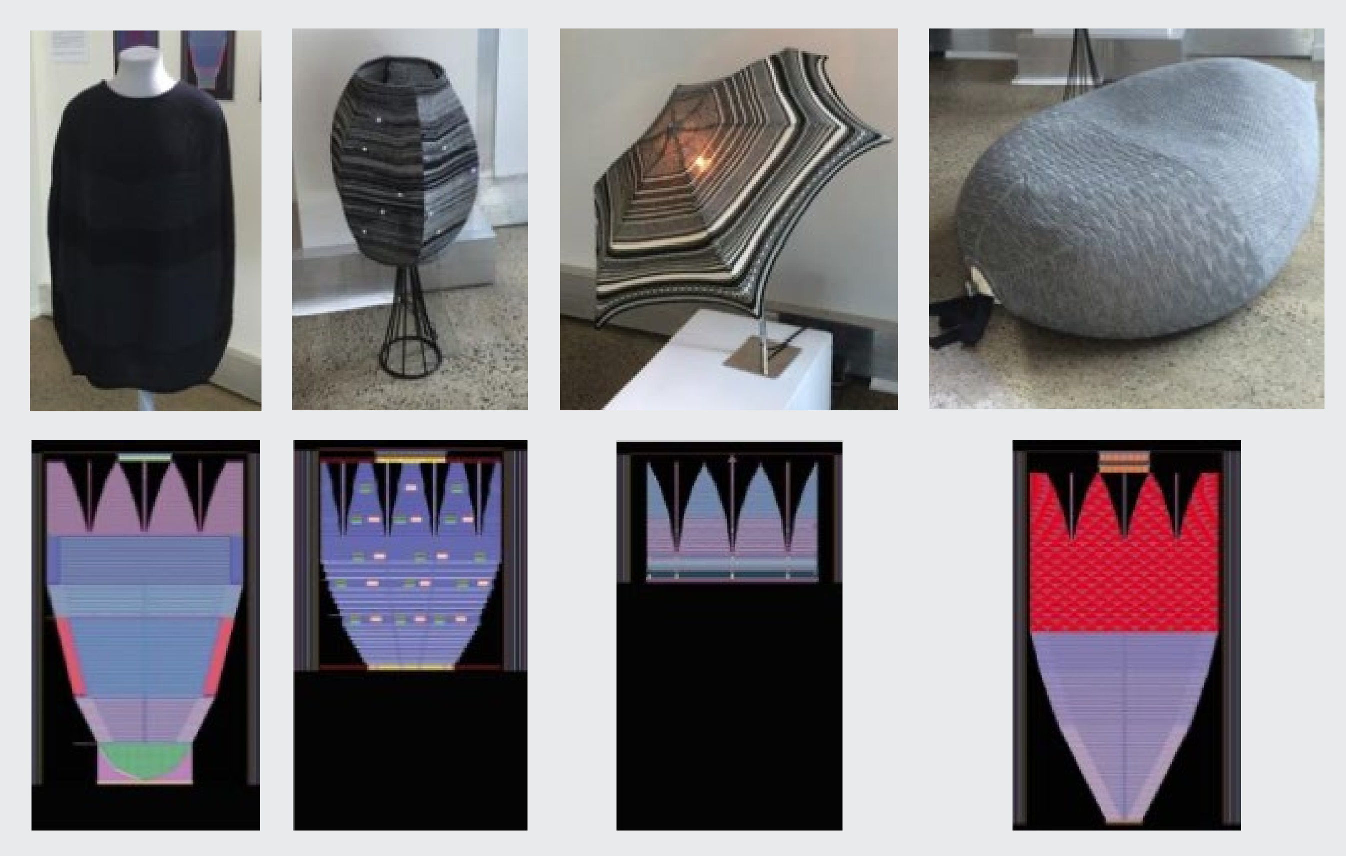


Figure 5.4
Knitted forms, Smith, Kalyanji & Fraser, 2014.

Figure 5.5
Knitted Fridge Cover, Nikolai Sorensen, 2015.

In evaluating the different projects, 3-dimensionality in knitted form was extended the furthest by a concept provided by an industrial designer (in the Knitted Fridge Cover project), adding weight to the suggestion that input from external experts will aid in shifting form-building from established knit-design practices (Nilsson, 2015). The 3-D Knit Transformations project, involving knit specialists with different areas of expertise, reinforced the complexity of the integrated elements within knitted-textile fabrication and the breadth of knowledge needed to successfully engage with the textile as a whole. The integration of electronic circuitry in the Sonic Textiles project demonstrated the additional functionality that can be embedded within knitted form, suggestive of the expanding potential of non-garment knitted forms that will result from improved access and an increasing range of functional fibres.

In this regard, all projects revealed aspects of the latent capability within the WholeGarment knit system and highlighted the opportunities that new participants can bring to the 3-dimensional knit environment. Despite these advances, the research did not continue along this path. The reason, in part, was the realisation that the complex process of developing product alongside design and materials experts, and managing such a process, was not familiar to me, potentially limiting how far the research could be extended. More significantly, within these projects early concept development had relied heavily on proven capability, especially with the time and cost constraints that often frame product-development projects. While a collaborative approach for the research inquiry would likely have resulted in a small range of functional, non-garment forms, it was the extension of capability, or more specifically, the lack of proven capability, that this research was seeking to address.

Further, the projects yielded additional findings and insights that informed the framing of the research. Perhaps most significant was consideration of and reflection on tools and processes that might support the reorientation of WholeGarment knit technology into a broader design arena. For example, the projects prompted questions as to how experts from other areas could be engaged and inspired in WholeGarment design and production, and how to shift thinking past the design fixation of established knit form-building practices. Further, the projects highlighted the difficulty for both knit and non-knit experts to understand the potential and constraints of WholeGarment fabrication, reinforcing the need for 3-dimensional form-building capability to be demonstrated more explicitly and in commonly understood terms.

Other aspects that would provide valuable avenues for research into the application of non-garment knitted forms, but were not able to be addressed in this research include:

Haptic and Visual Aesthetics

As for WholeGarment knitwear, haptic and visual aesthetic expression within textile surfaces of non-garment forms is also a sought-after attribute; this is further reinforced by the modules common to CAD software that enable colour, texture and pattern to be applied to designed skins or surfaces. The limited pattern and texture integrated within WholeGarment knitwear is addressed in Chapter Two, Application in the Knitwear Industry. As also noted there, this aspect of knitted-textile design requires further exploration in order to determine alternate patterning methods specific to WholeGarment fabrication.

Frames, Fills, Openings and Closures

As opposed to garment forms that clothe the human body, the knitted cloth of non-garment forms is likely to act as a surface for surrounding a frame or fill. As seen in both the Knitted Fridge Cover and 3-Dimensional Transformations, this requires alternative openings and fastenings to those utilised in garment forms. As WholeGarment technology is reoriented into a broader design arena it would be beneficial to explore options that would provide stable entry and exit points for frames and fills, flexibility of their placement on the knitted form, and methods for binding or fastening these points after frames or fills were inserted. The relationship of fibre and tactility of knitted cloth, and the material of its frame or fill also requires further attention, both with regards to effective combinations and the way each can react to or influence the other.

Technical Knitting[54]

In the interdisciplinary projects outlined here it was evident that the non-garment function of the knitted textile forms would have benefited from access to advanced yarns and technical knit expertise. With the increasing variation and functionality of knittable fibres allowing new possibilities for knitted cloth, aspects such as the interactions between form and yarn, and the notion of self-supporting yarns and structures that eliminate the need for fills and frames become central to innovative application. As noted in Chapter Two, Technical Knitting, while the range and utilisation of technical yarns is increasing, much of this development occurs in commercial settings where access to knowledge is restricted, leaving room for further exploration in this area.

Knit as Pliable Topological Surface

Does consideration of 3-dimensional knitted form as a pliable topological surface offer a new methodological approach to knitted form-building?

In this pathway topological surfaces were explored as a way to force a conceptual shift from the generation of knitted forms from known techniques, such as 2-dimensional flat patterns or the replication of 3-dimensional solid-state objects. In contrast to the solid-state 3-dimensional objects produced through technologies such as 3-dimensional printing, where the source material is intrinsically linked to the object's end form, 3-dimensional knitted textiles produce pliable surfaces. These surfaces can be manipulated into varied forms in line with the shape or tension activated by their frame or fill. More specifically, 3-dimensional knitted forms exhibit properties of topological surfaces. That is, the combination of knitted cloth emerging from a continuous length of yarn, and the seamless construction generated by WholeGarment knit techniques, allows for the textile surface to act as a continuous deformable plane, bounding a 3-dimensional space.

Belcastro (2009) provides a mathematical proof that every topological surface can be hand knitted. In attempting to translate this approach to a digital, seamless knit environment it was expected that previously undefined parameters and constraints of 3-dimensional form-building would be revealed. Further, as was Belcastro's (2009) intention for the knitted objects to be used as learning aids, here too the fabrication of forms would provide invaluable as tangible evidence of technical features and novel form-building possibilities.

Practice

The practice was first engaged in the development of a mobius strip, Figure 5.6, with iterative cycles of development focused on effective techniques for the necessary rotation of knitted surfaces. The rotation of a tubular form relies on the movement of edge loops from front to back beds or vice versa, such that the surfaces knitted on one bed are systematically rotated onto the opposing bed in a circular motion[55] – a knitting technique that I had not previously encountered.

In continuing with the forms presented in Belcastro's (2009) paper, the study moved to the construction of a Klein bottle.[56] The varied features and layers within the bottle would require several different construction techniques, for some of which the feasibility was unknown. Development began with an attempt to test whether each component could be constructed. The knitting of four layers simultaneously – which would be required multiple times within potential fabrication of a Klein bottle – was a technique I had previously considered impossible. However, a discussion with the Textile and Design Lab's technician raised the possibility of knitting at 1/4 gauge.[57]

As this development progressed, the significance of carriage directions in the layers of knitted form became apparent, with the fabrication of four layers simultaneously being achieved through varying techniques or sequences within the fabrication. Knitting two independent tubes simultaneously (Figure 5.7a) was easily achieved. However, the fabrication of independent tubes inside one another (Figure 5.7c) was more difficult to determine, with most techniques leaving one edge of the tubes joined (Figure 5.7b).

Figure 5.6
Mobius Strip knitted as a seamless form, 2017.
Left shows the join and subsequent twist created by rotating one needle bed only.
Right, the application of plain-purl texture removes the visual distinction between the two faces of the cloth.

Figure 5.7
Klein bottle development, 2017.

Technical Findings and Conceptual Insights

The limited exploration of this approach revealed unexpected fabrication potential, suggesting the fabrication of topographical surfaces as a method for exploring form building would yield considerable insights. However, the path was not pursued due to its dependence on the resolution of many aspects being carried out within a single form: a consideration that would leave limited scope for the diversity achievable in a broader range of forms.

Despite this, the approach yielded valuable insights which were taken into subsequent phases of the research. With regard to technical learning, the rotation of knitted surfaces across front and back beds is significant in that it is this technique that was utilised in the construction of spiral forms in Part Three, + spiral. Further, the ability to knit tubular forms at 1/4 gauge and, more significantly, the ability to fabricate four layers in parallel were also key. It is my belief that this technique could enable a significantly more diverse range of geometries than is presented within this research.[58] With the knitting of three layers previously considered a limit of the technology, the ability to knit four layers indicates the vast, unrealised capability of WholeGarment technology.

The most compelling conceptual insight emerging from this path was the shift in thought and perception with regards to conceptualising of 3-dimensional knitted forms. As opposed to thinking about form building in terms of a finished object, the shift to thinking about the continuous, deformable surfaces or planes that bound a 3-dimensional form allowed for a different spatial perspective when approaching the arrangement of planes in knitted geometries. This perspective is evident as an underlying principle in the fabrication of cubic geometries in Part 3, and again in the visual representations mapping form-building process in Chapter 6, Process Mapping.

Computational Literacy

Does a significant shift in computational literacy yield improved conceptual understanding of 3-dimensional form-building potential?

The part computational literacy plays in supporting the understanding of the WholeGarment knit system, and subsequent exploration of its capability, is a key foundation of this thesis. Most commonly, my technical understanding was incrementally increased through a self-directed, exploratory design practice. Less frequently, a key learning or insight would prompt a compelling change in perspective or knowledge such that new opportunities were revealed. Perhaps the most obvious example of this comes from my Master of Design research (Kalyanji, 2013). At the point in my practice where I understood the technology's capability to knit stitches, and therefore planes, at right angles, my perception of the possibility within the 3-dimensional form-building domain was substantially transformed. It is significant to note that this realisation came towards the end of the research project from studying the program of a slipper developed by Shima Seiki technicians. Study of the same knit program earlier in the research, before I had a level of literacy to engage with the programming, would have been unlikely to yield the same level of insight or understanding.

In this research, where the knitted cube is a known possibility, increased understanding of the fabrication of its planes and the parameters bounding its construction was expected to reveal opportunities for the form to be disrupted. More specifically, though the cube was proven, my understanding of its fabrication was not at a level where I was able to determine what else might be possible, or how to approach further exploration.

Practice

Underlying the computational literacy sought in this path was the intention to once again elicit a fundamental shift in my understanding of WholeGarment knit construction, in the expectation that such a change would offer a new perspective of 3-dimensional form-building possibility. The proprietary format of Shima Seiki's technology is such that formal training in its specialised software is only provided at the company's headquarters in Wakayama, Japan. I visited this training facility for three weeks (in February 2014), during which time I received one-on-one instruction, primarily in the programming interface of the technology. In addition, there were sessions on the use of the DSCS system,[59] and brief visits to other areas of the business and the design showroom.

Training at this facility is commonly reported to be highly structured, and thus constrained in both content and method of delivery (Underwood, 2009; Smith, 2013; Taylor, 2015). As I had established programming knowledge and was not concerned with the design or production of knitted garments, the training I received was focused on the programming interface of the software. Initially I was guided through the programming of a WholeGarment vest from set-up to bind-off, without the use of existing Shima packages. Though my own research was seeking to demonstrate non-garment capability, the programming of a garment from scratch, including required packages, was valuable in strengthening my technical understanding of machine movements and stitch formations, as well as advancing my programming skills.[60]

The programming of various features followed, each of which addressed different construction techniques or programming skills. For example, the addition of pockets required the knitting of three layers simultaneously, while the addition of a ribbed texture on the garment led to learning about the use of option lines to effectively apply patterning to a garment without interfering with its shaping.

It was towards the end of the visit that I was assisted in the development of non-garment forms derived from a cube. The industrial garment setting, and commercial parameters embedded within the format of the WholeGarment design system, were most evident in this phase of the training. The first variations explored were based on products already developed by Shima Seiki knit technicians, such as a tissue-box and seat covers. Initial attempts to determine the possibility of variations to the cubic form were stalled when I could not explain

Figure 5.8
Cubic form-building experimentation, Shima Seiki training.

the function or potential application of such a geometric form. In this aspect, the training seemed highly constrained. Though I cannot be sure of the cultural practices at play here, constraints appeared to emerge from two key concerns.

Firstly, it appeared that training was predetermined, and any deviations needed approval. Further, my instructor appeared intent on being able to provide me with an effective solution to my ‘problem.’ Any attempts to explore alternative forms were only permitted once a ‘solution’ had already been developed and tested by Shima Seiki technicians. Given my ‘problem’ was undefined and intended to be explorative (Buchanan, 1992), this aspect of the training was difficult to negotiate. In the limited time I did have to delve into more explorative variations of the cube, I was able to construct a small collection of samples that demonstrated adaptations on a single cube, as well as variations of repeating the form, Figure 5.8.

Technical Findings and Conceptual Insights

While not in the format I had expected, the training was invaluable in providing a significant shift in my knowledge, understanding and skill, effectively enabling a transition of my knowledge from a level of computational fluency to computational flexibility; a critical element in advancing the practice of 3-dimensional form building. The visit also reinforced the level of complexity inherent in the technology, with multiple teams with varied skills needed for the design and production of WholeGarment samples.

Also significant was the mapping of needle beds to 3-dimensional form in determining the dimensions and positioning of flechage on a cube. In the process of my instructor working through this mapping with me, we ended up drawing the flechage on a 3-dimensional sketch of the cube. The detailing of knit technique and shape onto a 3-dimensional sketch was significant in promoting the mapping of needle beds to planes in subsequent phases of this research.

Extending Computational Literacy: A New Perspective of the Knitted Cube

Does computational fluency offer new perspectives and understanding of 3-dimensional form-building?

Initially, the practice in this phase was focused on reinforcing learnings from the Wakayama training, with particular attention given to the fabrication of knitted planes. By way of replication, this process was intended to extend my computational literacy to a level of computational fluency. As discussed in Chapter Three, Computational Flexibility, this level of computational use represents understanding that enables a flexibility to build on existing practice. In this instance, with improved understanding of WholeGarment construction methods, particularly with regard to cubic form-building, it was expected that I would be better positioned to conceptualise further derivatives of the cubic form or, more specifically, identify opportunities within the fabrication of cubic planes in which the form could be modified or extended.

Practice

As I worked through the process of replicating cubic forms and re-examining programming and construction techniques, my understanding of the core elements of cubic fabrication improved and, in time, I was able to move past the proven geometric forms constructed at the training session. The expert skill that results from repetitive, practice-based, experiential learning is noted to be a “slow empirical process” (Dormer, 1994, p. 56). Similarly, Masterton (2007, p. 5, para. 5) writes that as for learning crafts, in learning to program “one learns through doing and through this process builds up a body of knowledge that enables more complex tasks to be achieved.”

Though significantly advanced, my understanding of the relationships between knitted planes was not yet intuitive and the incongruity between the 2-dimensional programming interface and the 3-dimensional knitted artefact remained a complex navigation. Programming of variants was a time-intensive exercise often requiring multiple iterations of trial and error as I continued to test and extend my understanding of the required translations. As a result, it was difficult to test concepts as they arose.

Further constraining experimentation was the lack of an established language or notation to represent 3-dimensional knitted forms. Documenting thoughts and ideas in a manner that was easily decipherable was problematic, and on returning to such reflections it was sometimes difficult to unpack the thoughts and their proposed response, especially with regard to how these applied to the 2-dimensional program.

Due to these challenges, there were limited fabricated knit artefacts that could be probed or examined, limiting the scope of the practice. With the intention of generating a collection of artefacts that could be analysed and contemplated in more detail, I sought out a means of rapid fabrication. In this setting, rapid fabrication was dependent on proven programming, and as such the forms generated drew from repeating and re-orienting existing cubic components to generate new compositions.

Technical Findings

In the evaluation of fabricated forms, the flattened and deflated forms as they came off the knitting machine made them difficult to assess both in relation to the program components and the intended geometry. Often, it was not until the form was filled that its 3-dimensionality could be accurately studied, or opportunities for variation considered. In these samples, set-up waste was left on the form to enable the start of the form, knit direction, and even ‘front’ and ‘back’ to be easily distinguished. Polyester stuffing was most often used to fill the forms and determine their effectiveness, though as the forms became more complex this became problematic, as the soft filling and the inherent flexibility in the cloth meant the shape could be manipulated in different ways, making the inherent geometry of the textile difficult to determine.

The key technical findings that emerged from this process informed subsequent developments that are outlined in further detail in other sections of this thesis: front-bed bias knitting (Figure 5.9), a ‘mapped’ form (Figure 5.10), and joins or hinges (Figure 5.11).

Conceptual Insights

The experimental practice in this phase allowed for further understanding of the tensions and relationships between planes in a cubic geometry, which, in turn, further reinforced the extent of the unrealised 3-dimensional form-building capability within the WholeGarment knit environment. Perhaps the most critical limitation was the enduring complexity of the mapping of 2-dimensional knit programs to 3-dimensional knitted forms. Even with increased understanding of the relationships between planes and the construction of the knitted form, the mental translations remained obscure.

In this regard, the forms that differed from their predicted geometry provided the key learnings as they challenged my personal perceptions and understandings of knitted planes and the parallel needle beds of WholeGarment technology, hence directing me back to the mapping of 3-dimensional form onto 2-dimensional programs. With such a time-intensive programming process, trial and error in this phase was a gradual, intermittent process, highlighting a need for better tools or methods for determining feasibility of forms before the lengthy process of programming.

Further, the need for language or notation to describe or depict 3-dimensional knitted forms was more evident in this phase as I attempted to describe findings or explain fabrication concepts to other practitioners, or to record these reflections as part of my own documentation process. The language used in my documentation often referenced elements of the form’s technical construction rather than components or planes of the 3-dimensional geometry. In part, this was due to the forms and their components not having explicit names that would readily identify the relevant sections of the geometry. Further, without function, the cubic form has no visible orientation, so aspects such as front and back are also difficult to identify definitively.

Figure 5.9

Front-bed bias.

The most significant finding in terms of revealing new potential was that of front-bed bias knitting. As a way of testing cubic components and determining how they mapped to the 3-dimensional form, the last plane of a cube was constructed using four different methods: with the bias moving left to right and vice versa, and with fabrication on either front or back needle beds.

Each method was found to be effective in closing the geometric form. Whether the bias was knitted left to right or vice versa had no bearing on the geometry of the form. The opportunity this did reveal was that the positioning of openings or bind-offs could be altered in the fabrication of the last plane.

Constructing the plane on the front bed, rather than the back bed that I had used in all previous fabrications, forced a return to the mapping of 2-dimensional programs and 3-dimensional forms. Stitches in the resulting plane were in a perpendicular direction to those knitted on the back bed, introducing the notion of orientation; something I had not previously contemplated. Though I was not fully aware of the potential this attribute allowed, it emerged as a significant aspect of the form-building geometries in the later stages.[61]

Figure 5.10

A mapped cube.

In order to create an artefact in which I could visually map and orient a 3-dimensional form to its 2-dimensional program, a cube was fabricated in which grey yarns were alternated for each area of the compressed knit program. Though useful under examination for determining which knit bed was used to fabricate each plane, the two colours were not sufficient to provide a simple visual mapping method to the compressed drawing. This issue was addressed in the multi-coloured instructive program and form developed as a learning tool in Chapter Six, Presentation of Research Findings.

Figure 5.11

Joins or hinges.

In the rapid fabrication of forms, repeating programmed components proved effective for extending forms. An interlock structure was used in these forms to join consecutive geometries.

Exploratory prototypes included variations in length of the joins, varied placement of openings (as had been revealed through the bias knitting in Figure 5.9), and varied placement and orientation of consecutive geometric forms.

Though the concept of 'multiples' motivated the form building, it was the joins themselves that proved an aspect of interest. In these samples the interplay between the inherent flexibility in the cloth and the tensions in the interlock joins between the geometries produces a natural directional movement and a further element to the 3-dimensional form.

This directional quality is more evident in the samples that contain both front and back bed bias knitting, as the directional changes in the stitches interact with the orientation of the form and the natural pull of its joins.

Though this aspect was not pursued directly in the subsequent stages of research, in its elementary form the interlock join was developed as a 'hinge' in the final catalogue of cubic forms.

With regard to investigating the knitted cubic form-building domain, the categorisation of components such as 'hinges' and 'front-bed bias planes' that can be embedded within 3-dimensional forms, advances the efforts to define and substantiate this space. However, each is accompanied by its own set of derivatives, which further extends the scope of verifiable knitted constructs. For example, there ar1e many versions of 'hinges' or 'front-bed bias planes' that could be integrated into cubic forms, just as there are many different sites in that form where this integration could occur.

Summary

The exploratory studies outlined in this phase all engaged with different approaches in seeking to incite a shift in perspective and surface new capability with regard to 3-dimensional knitted form-building. While only the path of technical literacy was extended, all approaches revealed significant insight, both technically and conceptually, and are considered feasible options for further research.

The extended investigation of cubic forms was most significant in its findings around front-bed bias planes; a capability that activated unexpected outcomes in knitted forms and that underpins a significant portion of the geometric forms revealed in the subsequent phases of the research. While effective for advancing the research, the self-directed, instinctive path followed in this phase led to the form-building domain being populated somewhat indiscriminately, with no definitive sense of its breadth or its bounding parameters. In response, the research adopted a more systematic and analytical approach to form-building for the subsequent phases of the investigation. This approach, detailed in Part 2, essentially established a methodical process for the investigation of 3-dimensional cubic geometries in the format of a cubic form-building system.

48 See Chapter Six, 3-Dimensional Knitted Form-building Development Journey.

49 For further detail on this research, see Alexander, C. (2015). Disabled monsters: Performing prosthetic technologies and ambivalent bodies. (Masters thesis). Auckland University of Technology, New Zealand. Retrieved from https://openrepository.aut.ac.nz/handle/10292/8883

50 For further information on this research project, see Smith, M., Kalyanji, J., & Fraser, G. (2014).

51 A narrowing technique which allows for even distribution of stitches across the width of a surface.

52 In using the word ‘forms’ here, the text refers to the design of the geometry, and visual and functional aesthetic, as well as the technical programming and construction.

53 As reported in https://idealog.co.nz/design/2015/01/keeping-kitchen-classy-good-cause

54 Chapter Two, Technical Knitting contains a more detailed review of this area.

55 On a technical note, construction of the form began with a closed tubular set-up with two layers of knitted surface knitted simultaneously but not joined at the edges. One of the surfaces was then held, while the other was rotated. After rotation, the simultaneous knitting of the two layers resumed before being bound closed. Racking of needle beds supported this rotation technique.

56 In 1882, Felix Klein imagined sewing two Möbius Loops together to create a single-sided bottle with no boundary. Its inside is its outside. It contains itself. Retrieved from https://www.kleinbottle.com/whats_a_klein_bottle.htm

57 Knitted stitches are formed on every fourth needle, leaving three needles between every stitch that can be used to hold or transfer stitches.

58 Of note, knitting at 1/4 gauge creates a different aesthetic and quality of fabric, with a looser fabrication. Technical knitting may help to resolve this, though suitable application of 1/4 gauge cloth would likely still vary in comparison to 1/2 gauge cloth.

59 Shima Seiki’s DSCS system has been outlined previously in Chapter Three, Understanding Fabrication.

60 It was also evident that in my being taken through this systematic form-building approach, my skill and knowledge levels were being assessed; each additional aspect of the form was only introduced once I had shown competency in the previous area.

61 For example, cubic geometric forms in Part 3, + ledge are often reliant on front-bed bias knitting to provide a change in direction of parallel planes. At this stage the construction technique was just used to close a cuboid. However, the technique also allows projection out from a cubic form.

Chapter Five

Part 2 - FOUNDATION FOR A FORM-BUILDING SYSTEM

Cubic Form-building System for WholeGarment Knit Fabrication

Defining a cubic form-building system for 3-dimensional knitted geometries

Operative	A category of geometric shaping distinguishable by both construction technique and resulting form
Attribute	Textual description and visual notations describing geometric shaping
Construction Technique	Textual descriptions of key construction techniques
Compressed Program	An instructive program in the format of Shima Seiki's programming language
Process Mapping	A mapping of front and back needle beds to 3-dimensional fabricated geometry
Fabricated Form	Knitted 3-dimensional geometric form

Considering an Alternative Form-Building Method

Can form-building methodology from another field be used to investigate and define possibilities within 3-dimensional knitted form building?
- Operative Design: A Catalogue of Spatial Verbs, Di Mari and Yoo (2018)
- Base cube and its segments

Compressed program as design template

Translation of volume to surface

Parameters and constraints of cubic fabrication

Variations on openings and closures

Orientation as a design parameter

Scale as a design parameter

Figure 5.12
Practice framework, Part 2.

Part 2

Foundation for a Form-building System

In Part 1 of this chapter it was seen that the cubic forms resulting from improved literacy and exploratory experimentation further validated the unrealised 3-dimensional form-building capability of WholeGarment technology. However, without a definitive indication of the range and breadth of such forms, or of the parameters bounding such possibility, form-building capability remained an ill-defined notion. Further, there was remaining uncertainty as to how to investigate and represent 3-dimensional knitted geometries.

In this second phase of the research, Figure 5.12, I endeavoured to reduce the degree of ambiguity surrounding WholeGarment knit technology's form-building capability by establishing a systematic approach to its investigation. The phase was defined by a direct and intense engagement with WholeGarment knit technology as the practice transitioned from exploratory and instinctive to methodical and analytical. As the practice advanced through iterative cycles of programming, fabrication and evaluation, tools, translations and articulations began to emerge, forming the basis of a 3-dimensional cubic form-building system.

This process was comprised of two key phases. The first phase, Considering an Alternative Form-building Method, addressed the need for a framework with which to further investigate the cubic form-building domain. Di Mari and Yoo's (2018) architectural text concerning spatial operatives was adopted as an approach to the inquiry. In line with the text, the making practices in this phase began with the development of a cube and its segments as base volumes from which derivative geometries could be explored.

In the second phase, Emergence of a Cubic Form-building System for WholeGarment Knit Fabrication, insights from the development of base cubes were consolidated with key findings from Chapter Three, Part 3, and Chapter Six, to form a cubic form-building system. As the research advanced, particularly through these phases of the research, incongruities between the operatives within the text and the form-building processes of knit fabrication were exposed. Further, as the geometries and their shaping components became more complex, tools and techniques to support composition of programs were further developed. As the practice responded to these complexities, a form-building system for 3-dimensional knit fabrication emerged. While not resolved until the end of the research, the system is outlined in this position within the thesis to provide an accessible framework for the investigation of cubic geometries presented in in Part 3.

Considering an Alternative Form-building Method

Can form-building methodology from another field be used to investigate and define possibilities within 3-dimensional knitted form-building?

In the discussion on form-building systems in Chapter Three, existing knit systems such as Underwood's Package Adaptation System (2009), or other more broadly adopted CAD systems from other fields, were considered incompatible with the investigation of an undefined domain. More specifically, the discussion addressed limitations around the reliance of these systems on known form-building components and, specifically with regard to CAD systems, the discord between methods of adaptation or manipulation compared to the distinct and continuous additive fabrication of surfaces in the WholeGarment environment.

As also noted in the previous discussion, the form-building approach adopted for this inquiry was instead informed by Di Mari and Yoo's text, *Operative Design: A Catalogue of Spatial Verbs* (2018), Figure 5.13. Intended for the shaping of form or space within the architectural field, the text begins with a cube as its base geometry and proceeds through a catalogue of operatives, or spatial actions, to generate a series of cubic geometries with suggestive derivatives. With the fabrication of a cube as a known capability, this method of form building offered potential as a strategy for determining if, and what, further capability there may be within the knitted cubic form-building domain.

As with CAD systems and Underwood's (2009) Shape Lexicon, this text could be viewed as a collated set of known components. However, it is the system for arriving at these geometries through spatial actions that is of particular interest within this research. While not directly translatable as a building approach, there were several elements of this text and its form-building system that aligned with the intentions of this research, essentially providing a strategy for the practice.

The research was initially motivated to replicate the forms in the text to determine knit fabrication capability. However, the shift to focus on operatives was quickly determined as incongruities between spatial operatives and additive fabrication were revealed.[62] In focusing on spatial action, rather than just the outcome of such action, the process of form building was highlighted, allowing for the generation of derivatives beyond the examples presented.

While structured and systematic, this approach is not prescriptive, but incorporated a flexibility that allowed for uncertain outcomes. The performative nature of the operatives and the format of their presentation (Figure 5.14) was suggestive, encouraging further exploration. A similar approach can be seen in Underwood's Shape Lexicon (2009, p. 165), which the author notes, "can act as a springboard for what is possible in terms of new ways of thinking about form, while remaining grounded in an understanding of what is technically possible."

Another concept common to both Di Mari and Yoo's *Operative Design* (2018) text and Underwood's (2009) system, is the use of multiple modes of representation for communicating the form-building process. In combination, these representations allow for differing perspectives and depth of understanding for each operative. Also, of relevance to this inquiry is that while the operatives and methodology of the text are focused on volume, the presentation of images as 3-dimensional line drawings illustrates the impact each action has on the surfaces of a volume (Figure 5.14). As it is the surfaces of volumes that are programmed and created through WholeGarment fabrication, the format of these illustrations allows insight into the required shaping components within the knitted planes.

In line with Di Mari and Yoo's (2018) text, the investigation began by establishing base cubic volumes to which spatial operatives could be applied. The following sections document this phase of the practice, with technical findings and conceptual insights discussed as they arose. Following on from this phase, the discussion turns to the development of a cubic form-building system for framing the investigation of 3-dimensional geometries within the distinct fabrication of WholeGarment technology.

Base Volume and its Segments

Di Mari and Yoo's *Operative Design* (2018) text begins with a cube as its base geometry. This volume is then dissected into segments that are used as entry points for establishing the cubic derivatives in the remainder of the text. In following this process, the research also began with programming and fabrication of a base volume and its segments. Despite most segments containing similar programming components to the 1/1 Base Volume, insight around scale and orientation was revealed through their development. Experimentation with openings, fills and closures of the knitted forms are also addressed in this next section.

1/1 Base Volume

As this research was concerned with the physical production of geometric forms, rather than their conceptual design as represented in Di Mari and Yoo's (2018) text, it was necessary to assign a unit of measure to the base volume (Figure 5.15). The units assigned, or the precision of achieving these measures within fabricated forms, was not as significant as the intention that the forms maintained a consistency in relation to the base volumes throughout the series. To explain further, remaining within the fixed range of the base volumes was

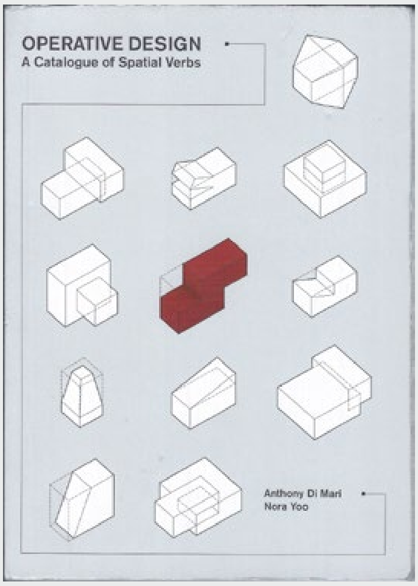


Figure 5.13

Operative Design: A Catalogue of Spatial Verbs, Di Mari and Yoo (2018).

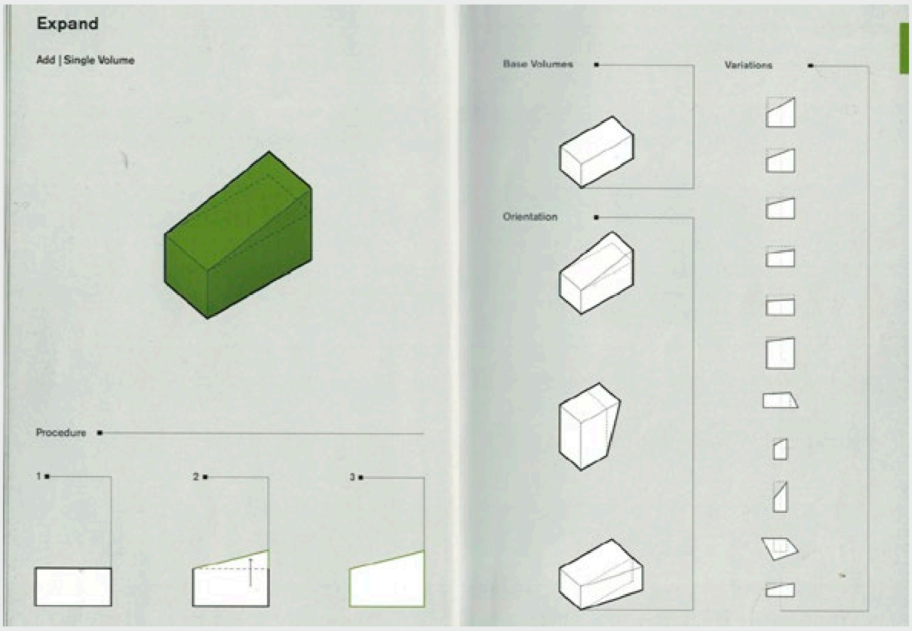
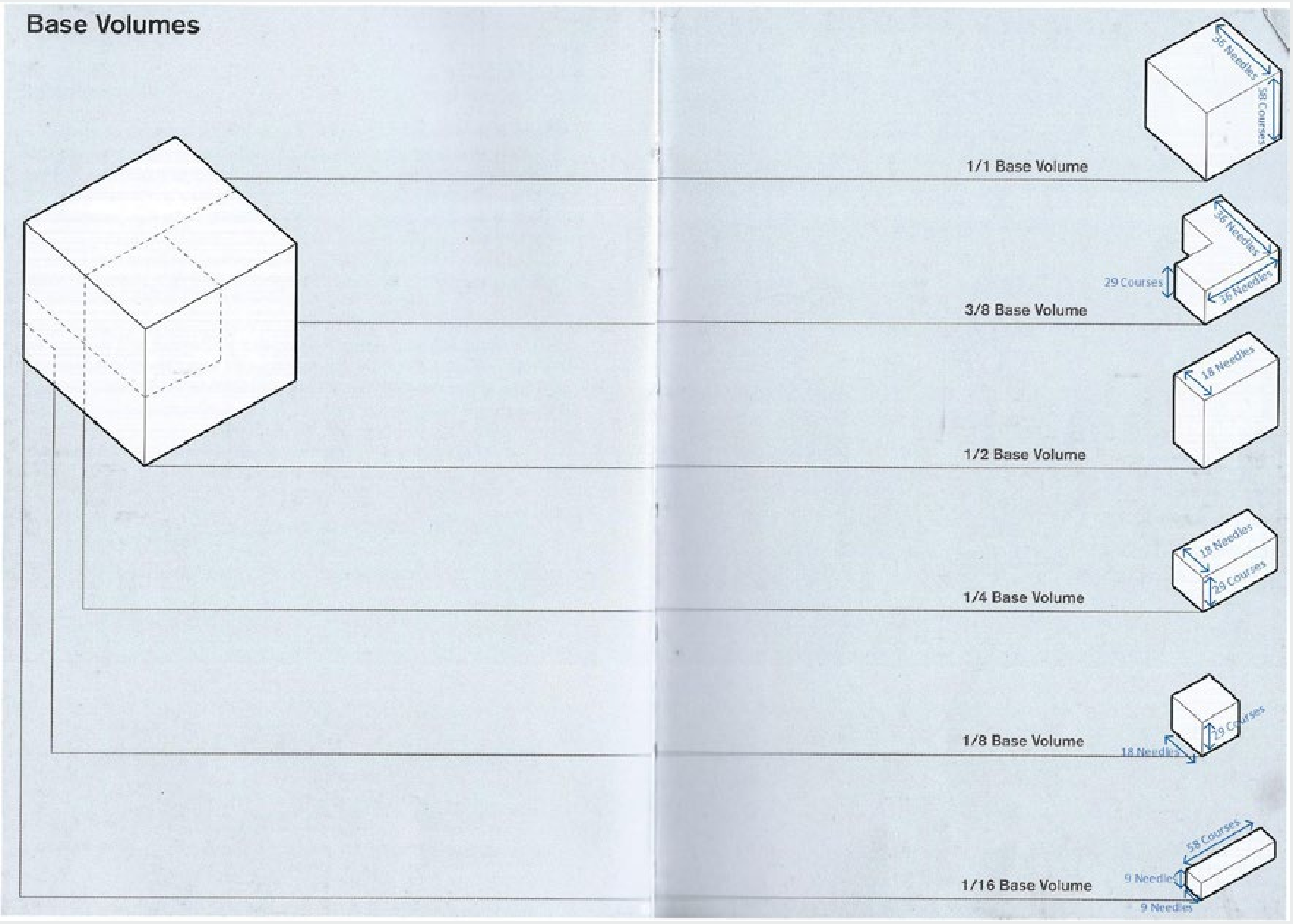


Figure 5.14

Expand, example of operative layout, Di Mari and Yoo (2018).



Figure

Base volume and its segments, annotated with desired measures, Di Mari and Yoo (2018).

beneficial in both the programming and the viewing of the fabricated forms. From a knit programming perspective, the consistency in dimensions allowed for program components to be reused throughout the range. This was especially useful given the additive nature of the WholeGarment fabrication technique, as the investigation of each new geometric form was likely to branch from, or be an adaptation of, a previously programmed form.

With regard to viewing the fabricated geometries, a consistency in dimensions allowed for presentation of a cohesive series deriving from the base volumes, facilitating a more direct comparison between and across the geometries, and simplifying analysis and evaluation of further developmental possibilities.

1/2, 1/4 and 1/8 Base Volumes

For each of these volumes the 1/1 compressed knit program was used as an entry point. In this instance, with the segments being smaller than those of the 1/1 Base Volume, the packages for each plane were reduced in width or height, or both. The dimensions of the segments and the corresponding translation to needles and courses was easily determined, allowing the required measures to be noted against the 3-dimensional sketches shown in the Figure 5.15. In this format, the dimensions were easily understood, and the required adjustments easily interpreted.

However, these adjustments were not as easily applied in the compressed knit program, as the 2-dimensional format of this program is not intuitively linked to the planes of the cuboid. The dimensions of knitted planes correlate directly to the needles and courses used in their construction, but the edges of these planes are not always explicitly represented within the compressed drawing, making it difficult to determine where required adjustments should be made.

More specifically, the segment of tubular knitting in a cuboid encompasses four planes, and therefore four vertical edges, spanning two parallel needle beds. In the compressed knit drawing, the width of the tubular knit package determines the number of needles being used on front and back beds.[63] Therefore, the left and right ends of the package correspond to vertical edges but there is no other indication in the central area of the package as to where the other two edges are. The same section of tubular knitting, as the sum of four planes, could represent a cube, with even length and width, or a rectangular cuboid, with differing length and width. It is not until this tubular section is viewed in relation to the bias knitting above and below it that its dimensions become clear.

Further, as mentioned in previous paragraphs, bias packages contain two courses of knitting on a single bed, requiring any adjustments to be applied as a multiple of two. As measures do not always divide by a multiple of two, dimensions are rounded up or down, and subsequently are not accurate to the exact needle or course.

In addressing these challenges, I annotated a compressed knit drawing of a 1/1 Base Volume (Figure 5.16). The intention was to use this as a visual reference showing the dimensions of a cuboid as they correspond with, and onto, the compressed drawing.

Though useful as a guide, the details of the specific scaling and adaptation of forms still required a mental translation and, with the need to ensure constraints of cubic parameters were met, miscalculations and oversights were easily made. To allow a more easily decipherable visual for the required adjustments I began to use copies of the 1/1 Base Volume compressed drawing as a template, recording the required adjustments onto the drawing itself (Figure 5.17). This process was effective in allowing a visual validation of adjustments before they were made onto the program itself. Further, in this format, the programming instructions were easily interpreted and applied.

1/16 Base Volume

The programming of this segment initially used the same knitting techniques and arrangement as the previous segments. However, some of the packages did not work with the smaller dimensions required, as the repeats built into the packages were larger than the required dimensions of the volume. In some cases, the repeat on existing packages could be reduced so that it was effective for both wider and narrower geometries. In others, new packages with smaller repeats were created.

One of the advantages of using packages is that any adaptations to the package are activated in every instance that the package has been utilised. This is especially advantageous when a package is found to be inefficient, as a correction to the package can be incorporated into every form that uses that package through the act of re-processing, rather than having to re-program each form. However, there is a risk in adapting the dimensions of a package or of its repeat units. That is, for any compressed drawings already programmed to required measurements, changes to the package dimensions or repeats could alter the dimensions of the developed knit programs and, subsequently, the fabricated form.

The best practice would be to retain the most efficient or effective package and adjust compressed programs as required. That being said, in the interests of conserving momentum in this experimental form-building phase, it was more often the case that new packages were created, avoiding the need to revisit the compressed programs of previously programmed forms.[64]

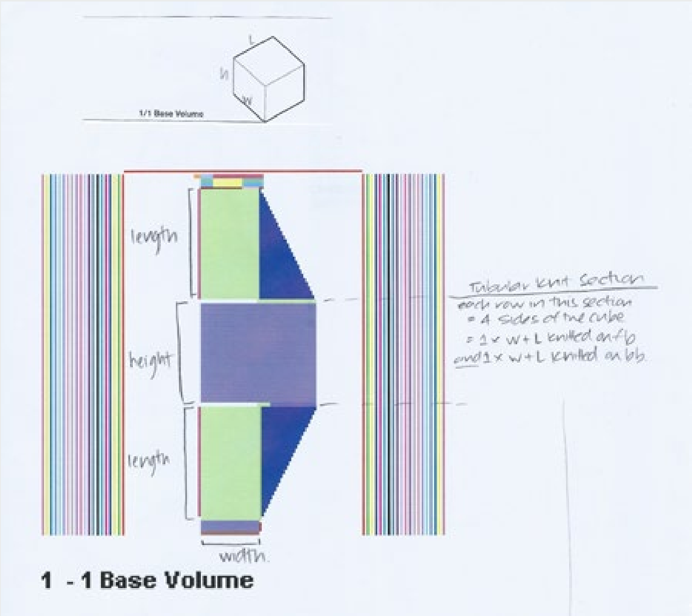


Figure 5.16
Base Volume, dimensional mapping, 2018.

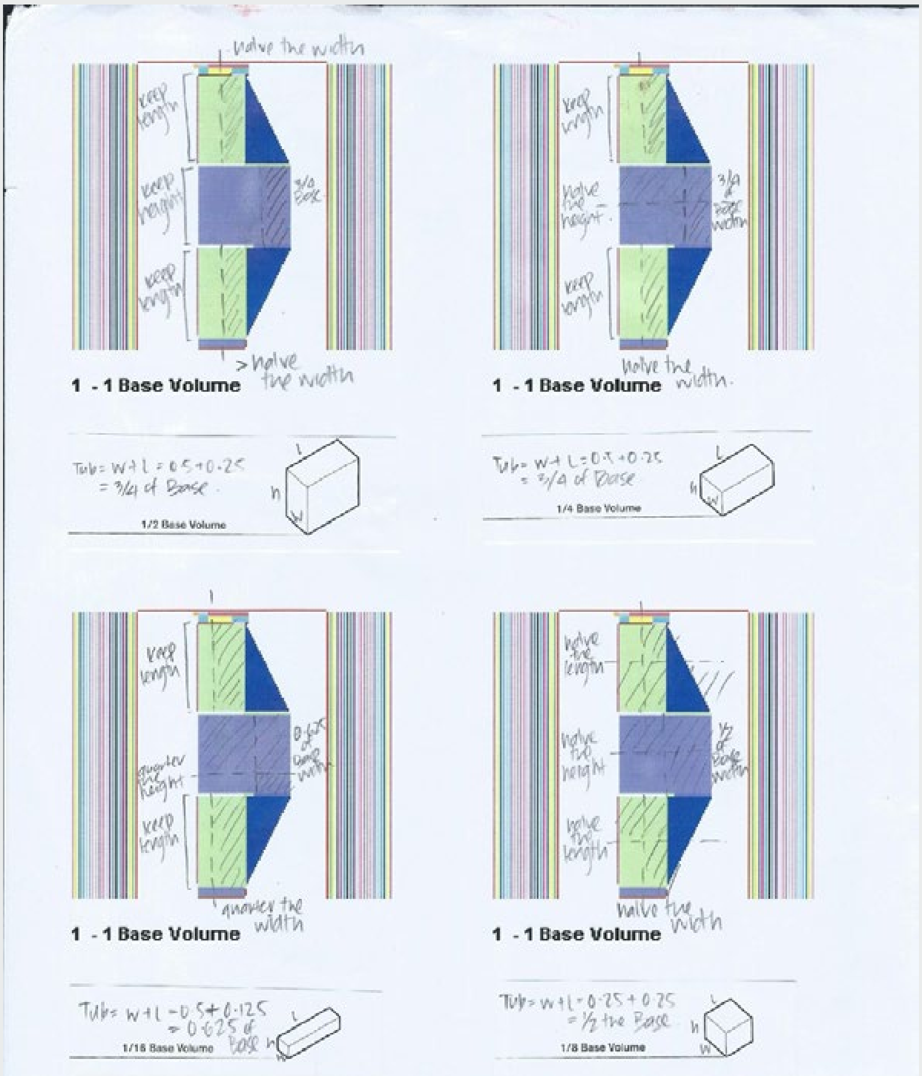


Figure 5.17
Base segments, dimensional mapping, 2018.

3/8 Base Volume

The 3/8 Base Volume differs from the other segments in that it is the only form that requires shaping in addition to scaling of cubic dimensions. The 'right-angle bend' in this volume is created by utilising short-row knitting techniques[65] within the tubular knitting area to create two mirrored cubic wedges. At the point where these wedges meet an internal corner is formed, which in turn generates the required right-angle of the volume.

The shaping for this form was difficult to map onto the 1/1 compressed drawing template. The geometry of creating an internal corner required short-row knitting within the tubular segment of the fabrication – a section representing four planes. The short-row knitting, or angular fabrication, was required on two opposing planes. Of the two remaining planes, one required no additional knitting and the other required the full height of the angle (Figure 5.18). This process was developed through trial and error, as my understanding of 3-dimensional fabrication was not yet sufficient to easily map the required translations onto the compressed program. Further, I had no established method for testing this graphically. In this form, orientation was also significant as the short-row knitting technique needed to be applied through the longest dimension of the form to be effective. For this reason, the 1/4 Base Volume form was reoriented, so that its length became its height (Figure 5.19).

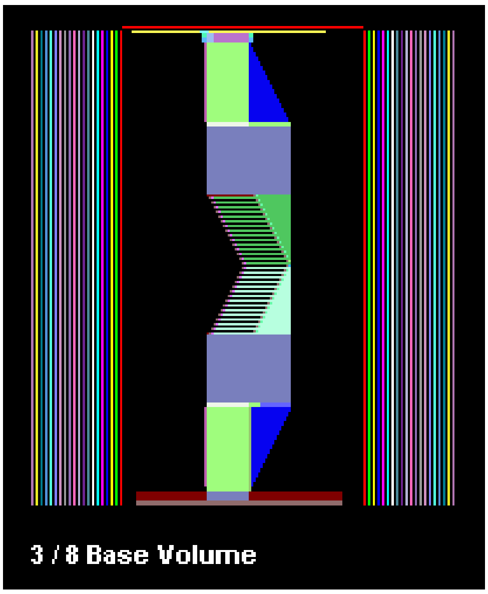


Figure 5.18

3/8 Base Volume,
Compressed Program, 2018.

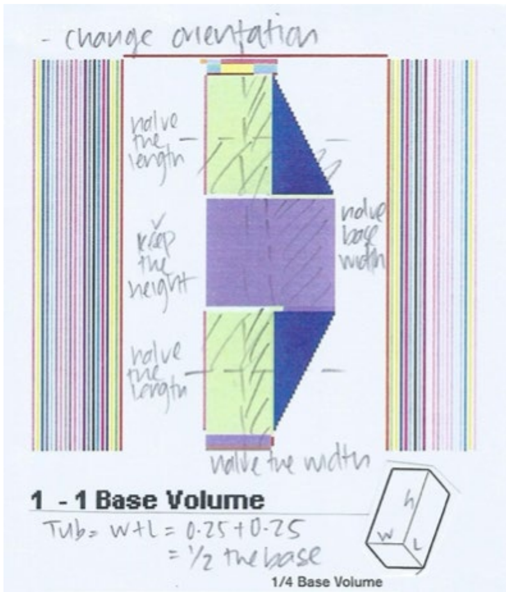


Figure 5.19

1/4 Base Volume,
alternate orientation, 2018.

Technical Findings and Conceptual Insights

The design and construction of the base volume and its segments (Figure 5.20) presented a number of technical and material considerations related to such aspects as scale, orientation, openings and closures. While not all these aspects are critical to the development of these base geometries, they became significant factors in the subsequent development of cubic derivatives. The technical constraints and idiosyncrasies of cubic construction that emerged through this phase are identified in the remainder of this section.

Scale

The unit of measure assigned to the 1/1 Base Volume for this research was a 10-centimetre square.[66] Programming techniques and packages for this geometric form had been established in previous phases. However, scaling the volume to a 10cm2 cube required a number of iterations. The two dimensions of a knitted plane are defined by, respectively, the number of needles and courses used in a plane's fabrication. As such, scaling of geometry requires adjusting the proportions of the packages corresponding to each plane within the compressed knit program. Though straightforward in concept, a number of variables can complicate this process.

First is the inherent flexibility in knitted stitches (especially using fibres such as wool), which can make it difficult to fabricate precise measures. Alongside this, a slight variation in stitch size can compound into a more significant difference in the dimensions of larger samples.

Further, the fabrication technique of knitted geometries and the corresponding parameters of cubic form-building introduce a new element to the process of sizing a knitted form (Figure 5.21). While the output of industrial machine knitting is largely in garment form, with all stitches fabricated in a single direction, the fabricated planes of 3-dimensional geometries contain stitches running in perpendicular directions. With specific reference to the cube, at the edges of planes for which stitches run perpendicular to each other, each wale intersects with the start or end of a course.[67] More specifically, at the intersection of bias and tubular knitting areas, each needle (and the width of its stitch) must align with the start or end of a row of stitches (and the height of that stitch). As a consequence of this parametric constraint, any adjustment applied to one cubic dimension impacts on the other dimensions.[68]

Lastly, potentially the most significant issue relating to the further development of cubic geometries was that of package repeats, and the need for the carriage to be returned to the left-hand side of the needle beds at the end of each section

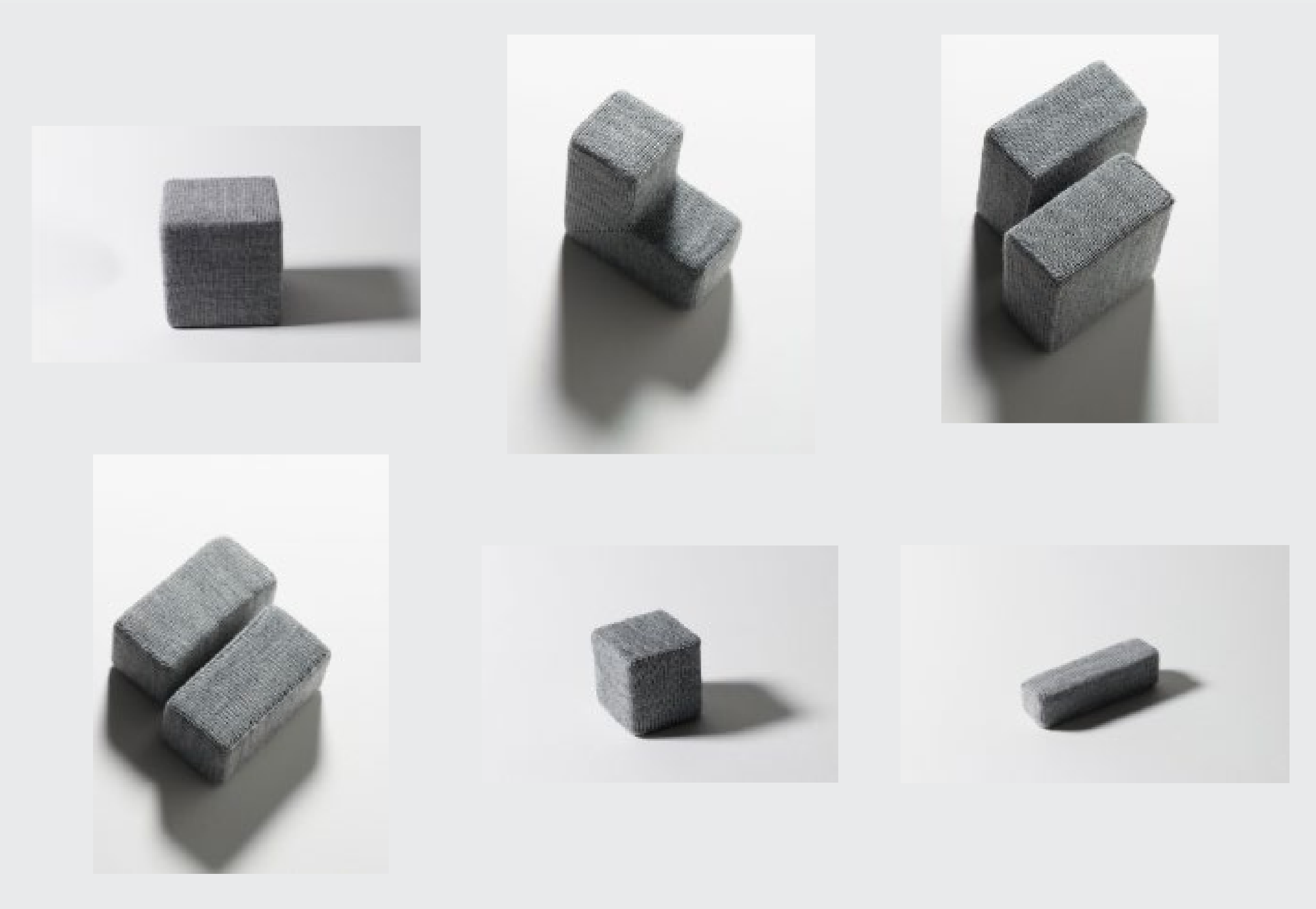


Figure 5.20
Base volume and its segments, *knitted and filled samples,* 2018.

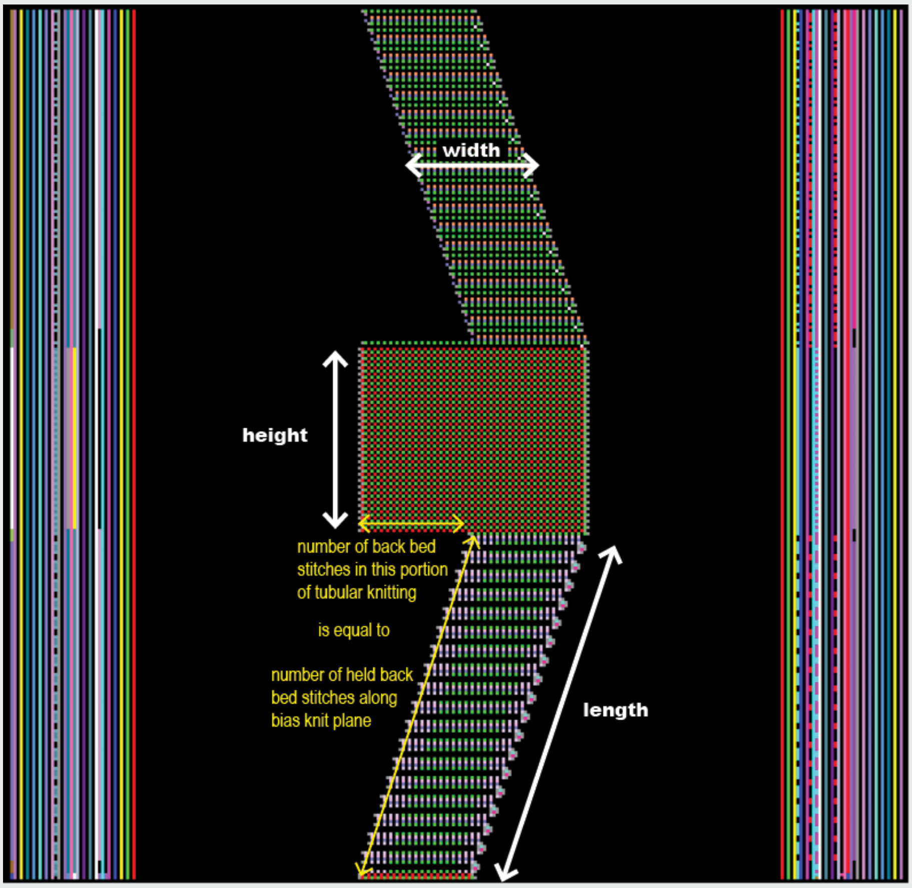


Figure 5.21
Example of parametric constraint for knitted cubic form-building, 2018

fabricated. This meant that changes to scale were not as direct as might be anticipated. For example, in the fabrication of the base volume and its segments, the package for bias knitting included two courses of knitting on the back bed only. Therefore, any adjustment to the dimensions of this knitted plane had to be a multiple of two knitted rows. In contrast, tubular knitting contains a single course on the front bed and a single course on the back bed, so it is possible to adjust dimensions of tubular planes by just one row of knitting[69].

Orientation

Following fabrication of the 1/16 Volume, it was evident that the opening was too narrow to allow filling. This prompted a return to the 3-dimensional sketch of the form and, in turn, consideration of the re-orientation of forms (Figure 5.22). In the case of the 1/16 Base Volume, assuming no change to the arrangement or order of the construction techniques,[70] tipping the form up so that its length became its height had no impact on the size of the opening. However, rotating the form on its base so that its length and width were switched allowed for a wider opening and for the form to be filled.

In this instance the re-orientation of the segment allowed for a wider opening, as required for the chosen method of filling the form.[71] As the exploration of geometries progressed, this notion of re-orienting forms proved to be a significant consideration in the development of cubic derivatives. For example[72], in some cases, the complexity of a form in conjunction with WholeGarment's additive fabrication technique meant a form could only be fabricated in one orientation.

Openings and Closures

Due to the additive nature of knitted form-building, and the desire to demonstrate 3-dimensionality as fabricated within the form, all components needed to be evaluated and integrated into the knit program before fabrication. For example, openings in the geometric form were required to be integrally knitted during fabrication. Further, as it was intended that programming components and

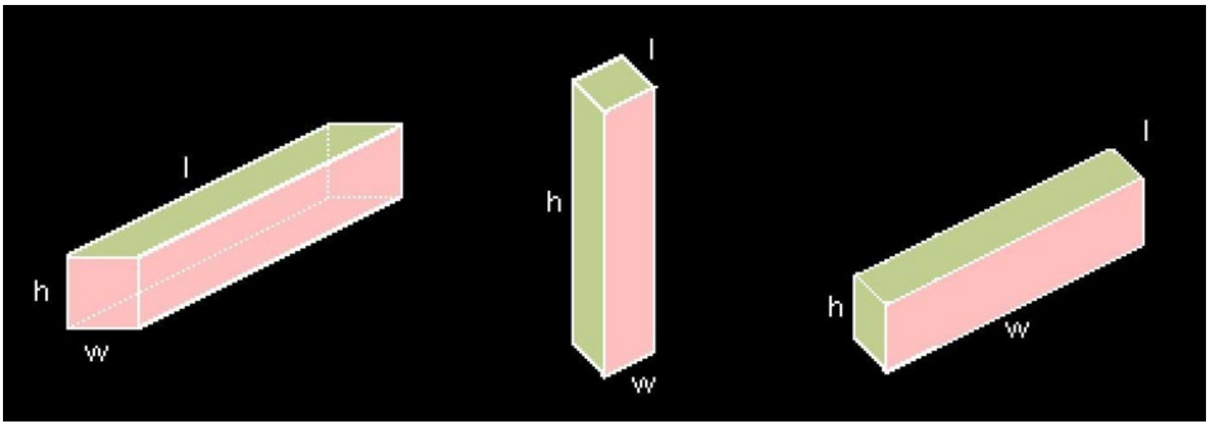


Figure 5.22
1/16 Base Volume, varied orientations, 2018.

packages would be repeated throughout the exploration, selecting the most effective version of these components earlier in the process avoided the need to reprogram and/or refabricate geometries.

Openings were required to be of a size that allowed the knitted form to be filled, but not to an extent that edges or corners of the geometric form could be affected, or that extensive amounts of hand stitching were required to close the form.

The forms fabricated in this research used four different opening techniques shown in Figure 5.23. Three techniques integrated an opening into the bind-off of the form. That is, once all planes of the form were fabricated, the stitches that remained on the front and back beds were bound off. Depending on the arrangement of the geometric form and the size of the required opening, either the last row of front- and back-bed stitches were bound so that the opening spanned the width of the planes (a), or the last row of front- and back-bed stitches were partially bound closed, with the remaining portion bound as open edges to allow a smaller entry (b) and (c).

The final technique for openings (d) used a c-knitting construction process to create an opening in the tubular component of the knitted form. Due to the nature of this construction technique, these c-knit openings are limited to those areas where there is no other textile shaping being applied. Furthermore, these were found to be more difficult to hand finish.[73] Therefore, these openings were only used if the composition of the geometric form resulted in a reduced width at the end of its fabrication, meaning the form could not be filled from the final edge, or if the arrangement of the form benefited from more than one opening.

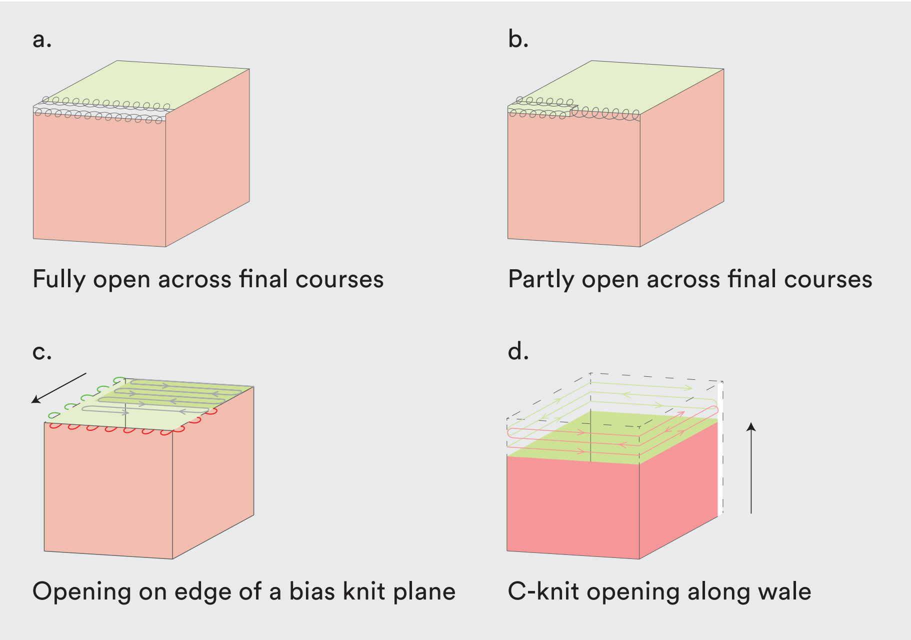


Figure 5.23
Openings, 2018.

With regard to the construction of the bind-offs, a number of variations were trialled. The tensions of tighter binds, though usually tidier and less visible, would often draw the bound edges inwards, giving the fabricated forms rounded corners. Thinner binds would roll more than the other options and were more difficult to hand-stitch closed. Efforts to stabilise the opening so that edges were flat and easily stitched closed included experimenting with ribs and plain-purl variations in the courses before the bind. However, the patterning this embedded within the fabricated form detracted from the geometry of the volumes.

To prevent distraction from the final form, the grey yarn used in fabrication was also used to hand stitch the forms closed after being filled. Though the intention was to be transparent with regard to the forms containing an opening and having been filled, experiments with decorative or different-coloured stitching highlighted the opening rather than the geometry of the form, leading to these methods of finishing being ruled out.

Materials and the Translation of Surface to Volume

A light grey merino wool yarn[74] was chosen for this investigation. This yarn contains sufficient strength and flexibility to be effective in shaped knit constructions, while the light neutral shade allows for the form to be highlighted both as a whole and in its detail, with regard to the direction of knitted stitches in each plane. Being able to easily identify stitch directions was useful in the mapping of planes from 3-dimensional form to a 2-dimensional programming grid.

With regard to the process of filling forms, this was also a point at which the form was evaluated against its intended geometric form. Though a form came off the machine complete, it was often not until it had been filled that proportions, orientation and angles between planes could be definitively assessed. In addition, filling the forms addressed the intention of demonstrating knitted form-building capability through an easily decipherable collection of viable geometries.

After some experimentation, a firm packaging foam was chosen for filling the knitted forms. This foam could be compressed to squeeze through the openings of knitted forms and had a density that retained the cut edges and corners of its intended geometric form, allowing visibility of the cubic shaping and proportions. Though sufficient for the purposes of this research, it is expected that the frame or fill of 3-dimensional knitted forms, and their subsequent finishings, could benefit from the knowledge and wider experience of practitioners in fields such as product design and textiles engineering.

As the geometries were extended and merged, their planes became more difficult to ascertain in their unfilled fabricated form. However, the translation from fabricated form, or programming dimensions, back to metric measurements required for cutting foam also became more complex. As for the challenging translation from 3-dimensional drawing to 2-dimensional programming, the reverse is also true. And, as additional cubic components were layered into the geometries and elements, such as angular areas integrated within the forms, the translations became more complex.

Further contributing to the complexity of this translation was that fabricated forms represent surfaces enclosing a volume. Though dimensions of each plane could be calculated from a knit program, these did not always directly correspond to the volume, or mass, of foam that the planes enclosed. For example, if a geometric shape contained plane(s) that did not run perpendicular to other planes, while the dimensions of the surface could be calculated from the knit program, this did not provide a direct translation to the measurements for cutting foam. Instead, the additional measurements and angles required were determined mathematically on a 3-dimensional sketch of the form.[75]

For the purposes of this research, a slight variance detected in the bias and tubular fabricated planes, or in the measure of its fill, is not significant. However, given the potential application of 3-dimensional knitted forms, and specifically non-garment forms, in broader domains, greater accuracy may be required. There are many aspects of technical yarns and technical knitting that could be utilised to reduce or eliminate variation in scale and embed required functional attributes.[76]

Summary

In the process of programming the base volume and its segments, a library of programmed components for the various planes and openings of cuboid forms was established. These components represent the various WholeGarment construction techniques used in the fabrication of 3-dimensional cuboid forms. As such, they form the basis for an expanding library of components for the investigation of cubic derivatives continued in Part 3.

Also reinforced through this process was the need for a framework, processes and articulation of 3-dimensional knitted form-building. For example, the 1/1 Base Volume template was effective for recording the required programming adjustments for most segments, and remains useful as a guide for diagrammatically demonstrating the parameters of cubic form-building. However, as part of a programming method, the template does not allow for shaping within the form or extension past the base volume, prompting the need for alternative methods and representations. These early insights were combined with findings from Part 3 and Chapter Six to establish a form-building system. The significance and development of the elements in this system are detailed in the following section.

Emergence of a Cubic Form-building System for WholeGarment Knit Fabrication

In the programming and construction of base volumes and segments detailed in the preceding section, multiple modes of representation emerged to support the conception and translation of the various geometries into knitted forms. While not initially recognised as such, the format of Di Mari and Yoo's (2018) text similarly presents geometries from a range of perspectives, reinforcing the value of such representational diversity. For example, the procedure for each operative is illustrated in flat drawings with directional arrows to suggest the performative operation, while both flat diagrams and 3-dimensional drawings are used to illustrate the resulting form and derivatives. Further reinforcing this concept is Underwood's (2009) Package Adaptation system,[77] which includes elements representing such aspects as program formats, stitch structures and fabricated forms for each design element documented.

In this research, the various components and representations of the cubic form-building system evolved directly from the practice in response to emerging needs and insights. As the practice advanced and the geometries became more complex, the need for multiple modes of representation within the system was also reinforced as established tools and techniques proved to be inadequate. These elements were subsequently tested within the iterative design cycles of the form-building investigation, allowing for refinement or reconsideration throughout.

While the system and its components are detailed in the following sections, the version[78] presented here was not established until the practice was completed. Further, it was through arrangement of the exhibition and from reflection after the event, that the final system revisions were made. However, in discussing this system at this stage of the text a more accessible framework is provided for the investigation of cubic operatives and their derivatives in Part 3.

The system consists of a set of operatives relating to design and fabrication of cubic knitted geometries. For each operative, five elements are used to describe its geometry and construction (Figure 5.24). These elements range in nature and function from broadly accessible design concepts to highly technical documentation with representations ranging from text-based descriptors to visual formats, including illustrative drawings and notations, photographic images and programming diagrams.

In providing a range of conceptual and technical elements, the system allows for engagement by a range of practitioners, both from within, and outside, the knitted-textiles field. Further, in combination, the range of elements and their linking throughout allows for some of the complexity in translations between parallel needle beds and 3-dimensional forms to be represented in simplified formats. To explain further, for each operative, the varying visual elements such as 3-dimensional line drawings, compressed programs and process mappings all reference the same fabricated geometric form. While the chosen form will be just one of numerous possibilities, the selection of just one is intended to demonstrate an elementary use of the operative, alongside the varying elements of its design and fabrication.

The following discussion of the system and its elements is illustrated with reference to the knitted cube, or specifically the 1/1 Base Volume developed in the previous sections. An overview of the system as it relates to the cube is shown in Figure 5.25. As well as defining each element, the discussion addresses its development and the rationale for its inclusion in the system.

Operative	A category of geometric shaping distinguishable by both construction technique and resulting form
Attribute	Textual description and visual notations describing geometric shaping
Construction Technique	Textual descriptions of key construction techniques
Compressed Program	An instructive program in the format of Shima Seiki's programming language
Process Mapping	A mapping of front and back needle beds to 3-dimensional fabricated geometry
Fabricated Form	Knitted 3-dimensional geometric form

Figure 5.24
Elements of the cubic form-building system.

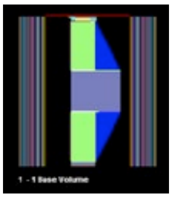
Operative

+ cube

Attributes

- a geometry of six planes, with each perpendicular to its adjacent planes

Compressed Program

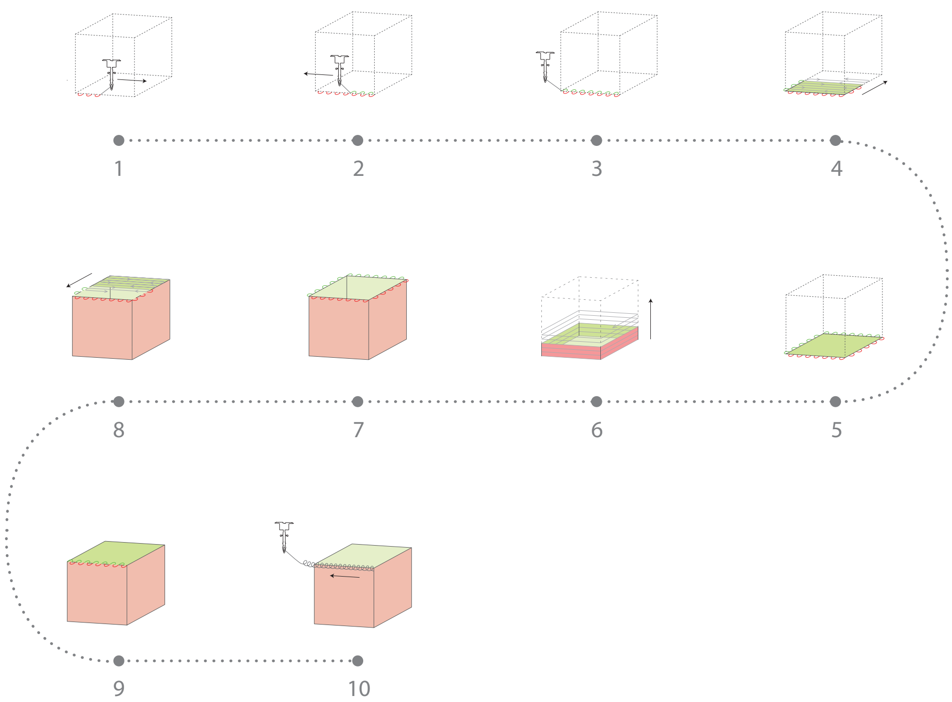


Construction Notes

- bias knit
- on front or back bed to create planes from different edges
- can be constructed with bias from left to right or vice versa

Fabricated Form

Process Mapping



knit on front bed

knit on back bed

surface constructed on front bed

surface constructed on back bed

loop held on front bed

loop held on back bed

loop knitted on front bed

loop knitted on back bed

outline of intended form

outline of constructed form

direction of carriage

direction of surface construction

binding off

X

Figure 5.25
+ cube, cubic form-building system, 2019.

Operatives

A category of geometric shaping distinguishable by both construction technique and resultant form.

Operatives are the primary element in the system of knitted form-building, incorporating both the distinct construction technique of WholeGarment fabrication and the material properties of pliable knitted surfaces. The need for operatives specific to the 3-dimensional fabrication environment emerged in response to the incongruity between the spatial terms in the *Operative Design* catalogue (Di Mari & Yoo, 2018) and the additive fabrication of knitted geometries.[79] This concern was surfaced and is documented throughout Part 3. The subsequent insights leading to the development of knitted cubic form-building operatives are discussed below.

With a focus on spatial explorations in architecture, Di Mari and Yoo write that the operatives, or spatial verbs, in the *Operative Design* text "are organised within a systematic framework to begin to differentiate how they operate volumetrically" (2018, p. 8). However, within the area of knitted form-building, where it is the surfaces of these volumes that are fabricated, these volumetric operations are not always aligned with actions or outcomes of the additive, stitch-by-stitch construction of knitted textiles.

For example, spatial verbs in the text that suggest a subtractive action, or that are used to classify architectural geometries perceived to have volume removed, can be confusing signifiers in that they do not embody the additive action utilised in the construction of the textile surface. Further, the pliability within the looped construction of knitted surfaces allows for planes of a geometric form to be manipulated in ways that solid substrates cannot. By way of example, this discord is explained in relation to terms in the *Operative Design* text (Di Mari & Yoo, 2018), Extrude and Carve (Figure 5.26).

Extrude is presented in the text as Add | Single Volume and *Carve* as Subtract | Single Volume.

However, as the continuous surfaces enclosing these volumes are unfolded it becomes apparent that, other than in their proportions, these forms are identical. In the WholeGarment knit environment they can be fabricated using the same technique and then manipulated through folding to create either *Extrude* or *Carve* (Figure 5.27).

As the investigation of fabricated geometries in Part 3 was extended, findings relating to specific construction methods began to guide the exploration.

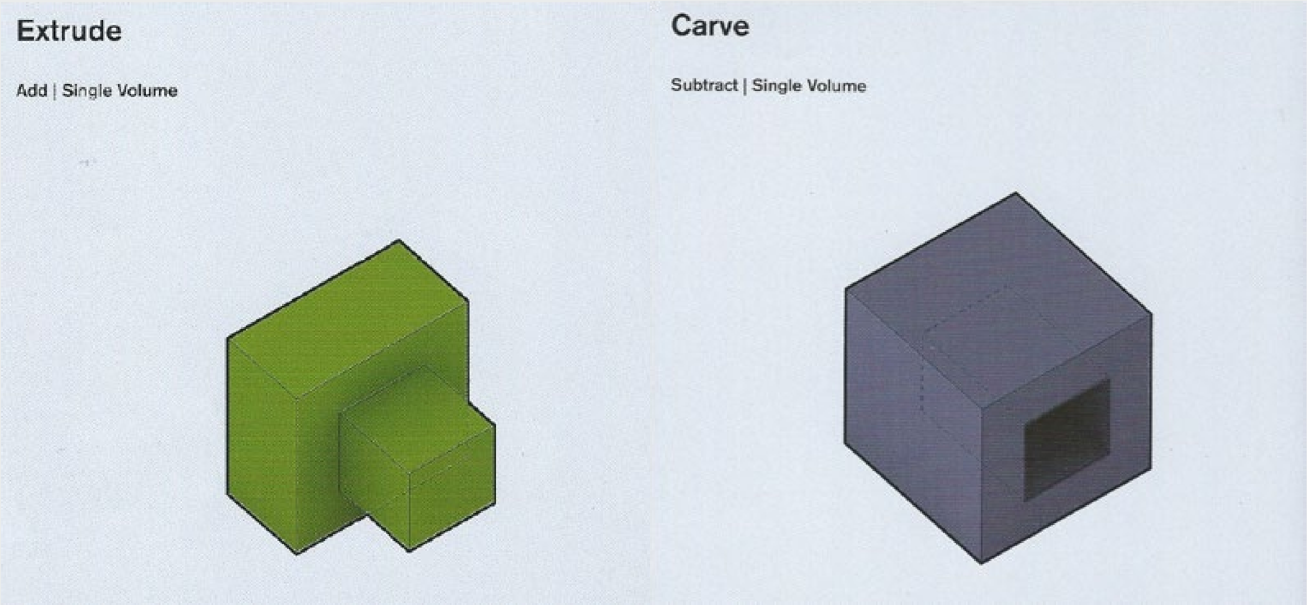


Figure 5.26
Extrude and Carve, Di Mari and Yoo (2018).

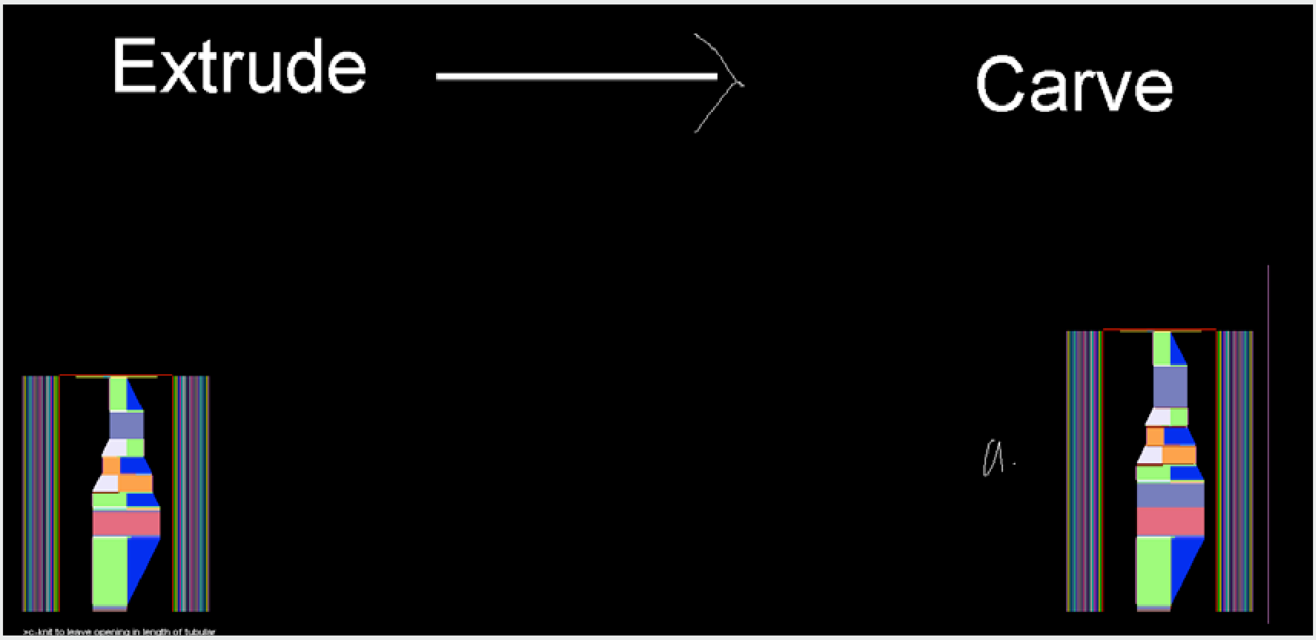


Figure 5.27
Extrude and Carve, Programming, 2018.

Each method identified allowed for additional series of geometries to be fabricated, so that the construction methods were guiding the sequence of practice rather than suggested groupings within Di Mari and Yoo's (2018) framework. Subsequently, this sequence, and the recording of such in a spreadsheet (Figure 5.28), began to reveal categories for the cubic geometries, with the incongruity between spatial operatives and knit fabrication becoming more apparent as the sheet was populated.

In addition, a text-based language was emerging for the description and evaluation of fabricated forms in their developmental stages. Documentation and consideration tended towards the use of knit terminology or, more specifically, construction terms, such as flechage, bias knit or holding stitches. However, while these descriptions could be interpreted by a knit practitioner in a programming or construction context, they do not provide an immediate sense of the geometric form they create, and are even less suggestive for and decipherable by the broader design audience whom 3-dimensional knit fabrication is intended to reach. For newer terms such as bias knit, the lack of documented use means they do not bring to mind any particular knit component or form. In contrast, more established terms such as flechage have a more instinctive association with the shaping they generate within garments and accessories; a shaping that often differs in visual effect when applied within a 3-dimensional geometric form.

In the earlier discussion in Chapter Three, Language of 3-Dimensional Knitted Form the need for more accessible and relevant language or notation was raised, with the objective of establishing a more broadly understood terminology. In the case of the operatives, the intention was to establish terms that provided an indication of the additive knit technique as well as being suggestive of the form or geometry being fabricated, regardless of focus on volume or surface. In the large space of a gallery, where the artefacts were being arranged for exhibition, and over some days, the groupings and techniques of the geometries were reviewed and revised, and the language identifying each group evolved from technical knit terminology into more broadly understood design terms (Figure 5.29).[80]

Category	Unit	Operative	Version	Programmed	Knit
Displace	Single	Split	D	as for branch? or introduce new feeder and pick up 4th layer	
Displace	Single	Twist	A	x	x
Displace	Single	Twist	B	x	x
Displace	Multi Volume	Shift			
Displace	Multi Volume	Intersect	A	x	x
Displace	Multi Volume	Intersect	B	x	x
Displace	Multi Volume	Intersect	C	x	x
Displace	Multi Volume	Interlock		Not clear if possible	
Displace	Multi Volume	Lift	As for Extrude		
Displace	Multi Volume	Overlap	A	x	x
Displace	Multi Volume	Overlap	B	x	x
Displace	Multi Volume	Rotate	A	x	x
Subtract	Multiple	Inscribe	C	x	x
Displace	Multi Volume	Lodge	A	x	x
Displace	Multi Volume	Lodge	B	x	x
Subtract	Single	Carve	A	x	x
Subtract	Single	Carve	B	x	x
Subtract	Single	Carve	C	try programming with flechage at end to create 3/8 volume type configuration	
Subtract	Single	Compress	See inflate		
Subtract	Single	Fracture	Is a combo of other pieces		
Subtract	Single	Notch	A	x	x

Figure 5.28
Spreadsheet documenting experimentation, 2018.

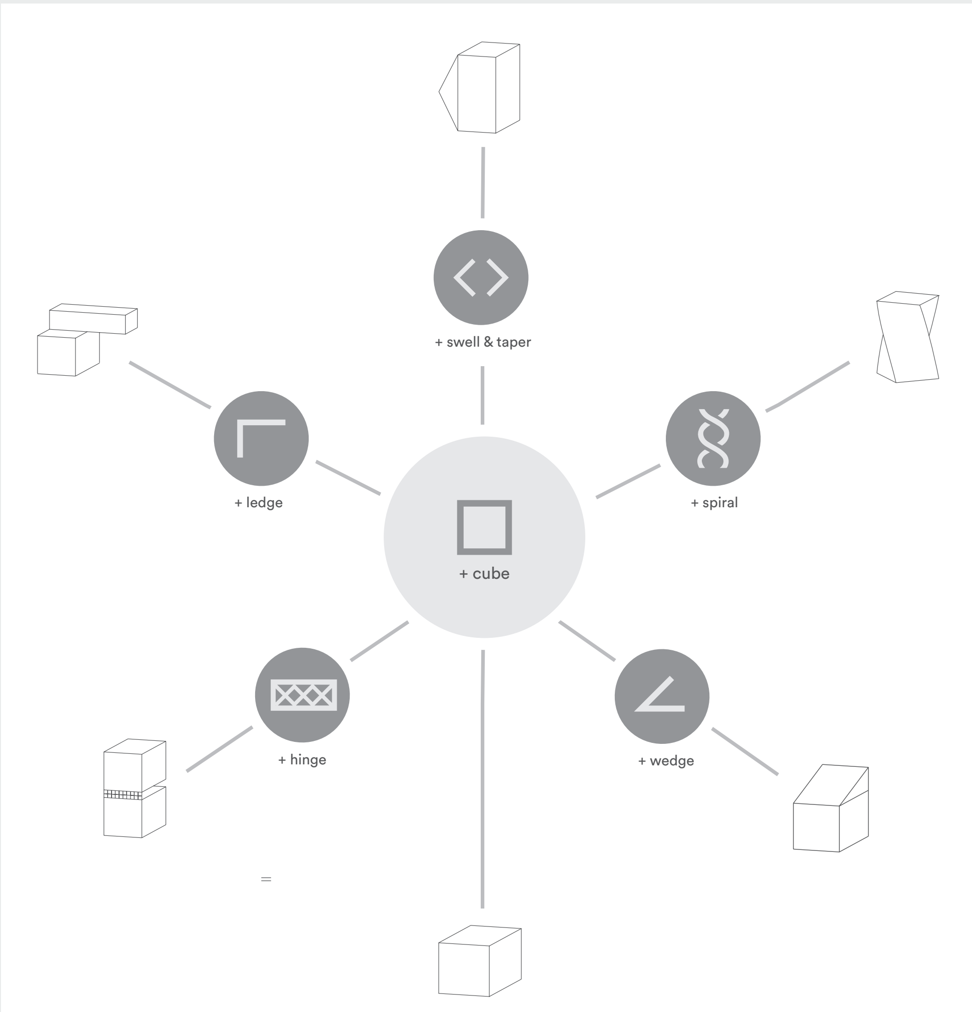


Figure 5.29
Operatives (+ ledge, + swell & taper, + spiral, + wedge, + hinge), 2019.

Attributes

Textual description and visual notations describing geometric shaping of an operative

As discussed in the previous section, the operative groupings and naming were intentionally shifted from being purely technical or domain specific to more generic and broadly understandable terms. However, when considered in the context of a broader design audience, or those unfamiliar with the WholeGarment manufacturing process, these terms alone are not explicit in their meaning and remain open to misinterpretation or confusion. Therefore, the element of 'attributes' provided both textual description and visual notations to support interpretation of the type of shaping, or geometric form, within each operative. The textual descriptions are brief, highlighting characteristics of the form or its fabrication that distinguish it from the other operatives. In addition, two graphic representations, or notations, were developed to provide a visual cue to the shaping that can be achieved through the utilisation of the operative and an illustrative reference of a resulting geometric form.

In the first representation (Figure 5.30), symbolic icons were developed to help define the structure or shaping associated with the textual label of each operative. As easily replicable drawings, the icons can also be used as a visual language for documentation such as in describing, identifying or planning geometric fabrication. An example of this application is shown in the labelling of compositions in the Catalogue of Cubic Geometric Forms, Appendix B (Figure 5.31), whereby a combination of icons is used to describe each geometric form. The use of these symbols essentially provides a visual mapping of the various operatives used in the production of that form, reducing the need for a more extensive text-based name or description.

The second representation is that of line drawings with 3-dimensional perspective, (Figure 5.32). While the symbolic icons offer a sense of the shaping each operative allows, these line drawings are more illustrative, hinting at the 3-dimensional forms that can be fabricated within that grouping. Further, these outlines are replicated in the process mappings addressed later in this section. As such, their inclusion in this diagram links each operative with a visual mapping of its fabrication process.

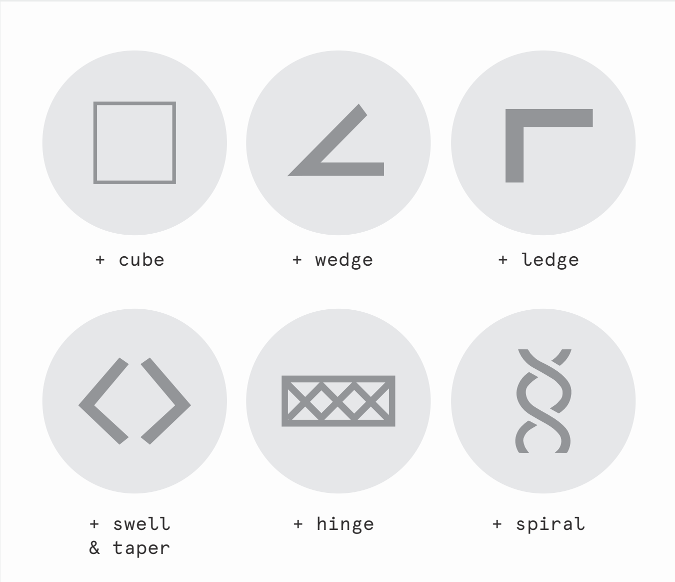


Figure 5.30
Symbolic icons for operatives, 2018.

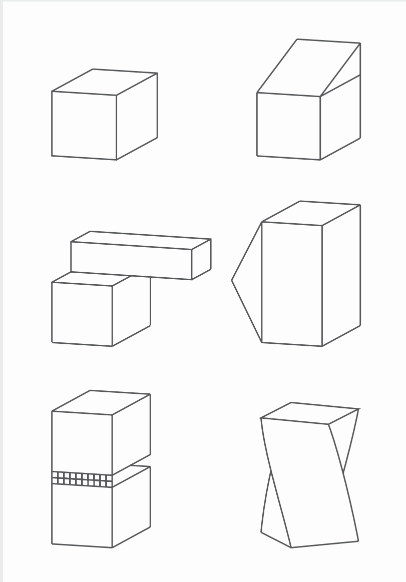


Figure 5.32
3-Dimensional line drawings, as illustrative reference of resulting geometries, 2018.

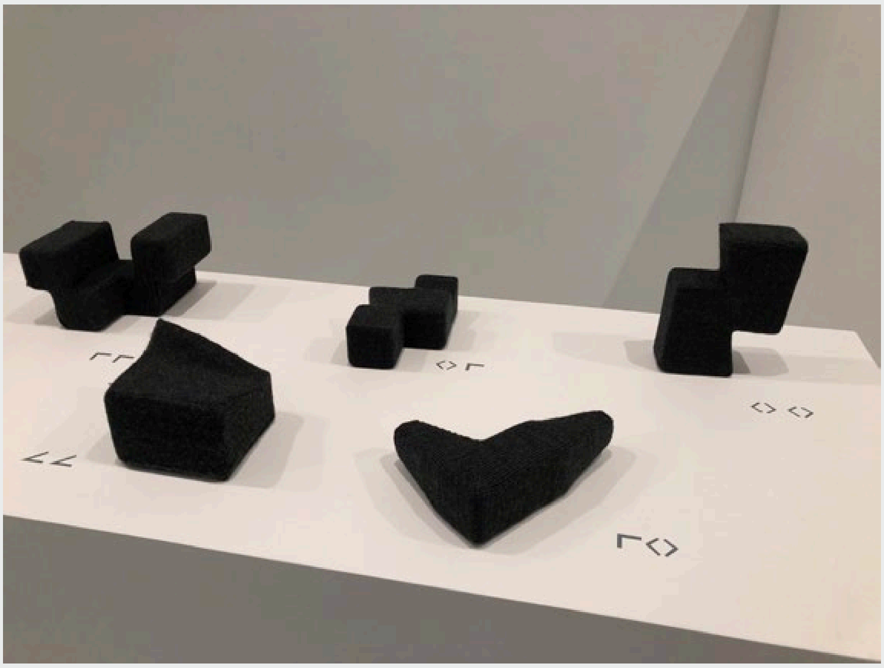


Figure 5.31
Labelling of compositions with operative icons, 2018.

Construction Techniques

Textual descriptions of key construction techniques

As a more technical element within the cubic form-building system, the construction-technique descriptions provide insight into the means by which the operative shaping is embedded within a 3-dimensional geometric form In this regard, the construction notes also provide guidance as to the placement or composition of the techniques within a program.

While a knitted cube can be fabricated in multiple ways, all methods contain the same core construction techniques. Variations in fabrication methods result from altering orientations, or the sequence of these techniques, rather than alternative methods for creating planes. As such, the techniques are provided as brief descriptors. A more comprehensive key of construction techniques is provided in Appendix A, Form-building Manual, and shown here in Figure 5.33.

While most of these techniques are commonly used within WholeGarment knitwear, the explanations and insight provided relate specifically to the way in which they are incorporated within cubic forms. Where possible the techniques are identified according to common knit terminology or terms from the Shima Seiki design software. In cases where there is no common name, as for ‘bias knitting,’ they are referenced according to the label I applied throughout this practice documentation.

Of note, it is the element of the bias knit planes that introduces another dimension to form building, allowing attachment capacity and essentially acting as a mechanism for connectivity of planes within the form. When used in combination, the bias knit techniques instil the directional stitch movements seen within the fabrication, and which subsequently inform the structure of the 3-dimensional geometries.

Construction Techniques, Cubic Geometric Form

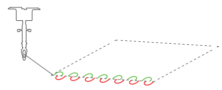
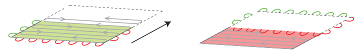
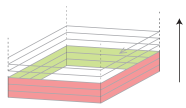
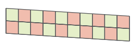
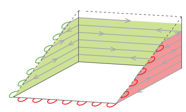
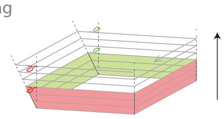
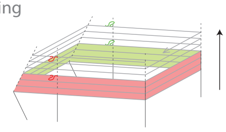
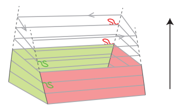
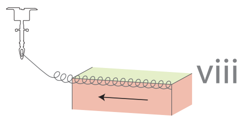
Construction is initiated with a closed tubular set-up. The width of this row of knitting is equal to the starting width of the cubic form. This set-up row could be adapted to an open tubular set-up to allow an opening into the form. Different set-up techniques offer different finishes with regards to elements such as visual aesthetic and stability.	Set-up Row 
Construction occurs on a single bed in a diagonal direction. The diagonal direction allows for a plane to be constructed such that the right and left side edge loops on each row of knitting are held as the plane is fabricated. The held loops form the edge of a cubic form, whereby tubular knitting following the bias fabrication is constructed in a perpendicular direction to the bias knit plane. Bias knitting is used to construct the top and bottom planes of a cube, with the width of a bias knit plane being equal to the width of a single plane.	Bias Knitting 
Circular construction spanning fabrication on front and back beds. The first row of tubular construction picks up the held loops left by the bias knit plane. Stitch direction is perpendicular to the bias knit. The width of front and back bed fabrication always even in length and in combination is equal to the width of four planes. However, not all planes are necessarily the same width. That is, the same tubular construction can be a square cube or a rectangular cuboid. The width and length of the bias knit plane before the tubular, and hence the lengths of the held loop edges inform the width of the tubular planes.	Tubular Knitting 
An independent component creating a join between two geometries. In this research an interlock feature was used. Variations could include stitch type, proportions and shape of the join.	Interlock 
Short-row knitting allows for loops to be added in some areas of the knitted surface and held in others. The proportions by which rows of knitting are shortened creates differing dimensions in the wedge that is created.	C-knit 
Inside widening within a tubular segment of knitting. The construction technique introduces additional loops within a plane or surface rather than at is edges. Additional loops are added within a course of knitting. In this geometry the same number of loops are added to both front and back beds, though the positioning of the loops may vary.	Inside Widening 
Inside narrowing within a tubular segment of knitting. The construction technique reduces loops within a plane or surface rather than at is edges. In this geometry the same number of loops are reduced on both front and back beds, though the positioning of the loops may vary.	Inside Narrowing 
A combination of racking and transfer of stitches across needle beds creates a rotational or twisting motion within the tubular segment of a geometry.	Rotation 
The last front and back bed rows are locked such that they cannot unravel. A bind off can be used to close a form by joining the front and back bed edges, or the edges can be locked separately so that the form remains open. A combination of the two is also possible. Different bind-off techniques offer different finishes with regards to elements such as visual aesthetic and stability.	Bind-off 

Figure 5.33
Construction techniques, cubic geometric forms, 2018.

Compressed Program

An instructive program in the format of Shima Seiki's programming language

The Compressed Program (Figure 5.34) is a Shima Seiki specific software representation of programming instructions. Detailed previously in Chapter Three, WholeGarment Design and Production, this format represents an encoded program of packages for the fabrication of a 3-dimensional geometric form.

As seen in the previous section, Construction Techniques, this element is one of the more technical in the system and could be seen to represent a seemingly abstract relationship between the 2-dimensional programming grid and 3-dimensional geometric form. Also of note is that the program is open to interpretation, given that it is composed of 'packages'[81] of encoded data. Without a database of the utilised packages, the programs cannot be unpacked or fully developed. However, as noted previously, it is the combination of elements for each operative that provides a comprehensive view of its fabrication.

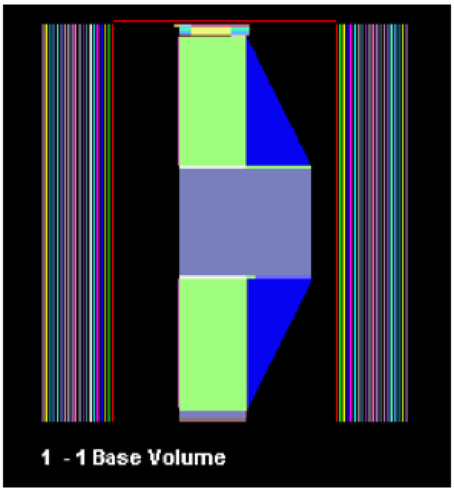


Figure 5.34
+ cube, compressed program, 1/1 base volume cube, 2018.

For an experienced knit practitioner, the compressed program provides an indication of shaping technique and the positioning and sequence in which it is applied in the fabrication of a cubic form. Further, as was illustrated previously in the development of base volumes, it is the compressed program, rather than the developed program, that forms the template on which revisions and derivatives are programmed.

To explain further, all geometries in the cubic form-building investigation started with the compressed program for a base cube or one of its segments – initially the only proven components of programming. Each time the investigation of a construction technique for extended form-building was found to be effective it was codified into a package. In turn, this established an additional component that could be integrated into base or segment cube programs as required for an intended geometric form.

However, none of these packages can work in isolation; rather, each represents a specific construction technique that can be nested between other packages to create a functional knit program. Consequently, the compressed program of the initial cubic form becomes a baseline with multiple points of departure. At each departure point, component packages can be merged or integrated into the program, generating an extended program for a derivative geometric form.

Process Mapping

A mapping of front and back needle beds to 3-dimensional fabricated geometric form

The absence of mechanisms to support the translation and transitions between 3-dimensional fabricated form and parallel needle beds or 2-dimensional programming grids has been discussed previously. The initial use of compressed programs as a template, detailed in the development of base volumes (Figure 5.17), was shown to be inadequate for representing shaping beyond the scale and orientation of a base cube. Therefore, the development of knitted geometries was continuously engaged in oscillating feedback loops as thought shifted between 2- and 3-dimensional manipulations of textile surfaces. Through this process tools and techniques evolved to address the connections and dependencies between constructed 2-dimensional surfaces and the 3-dimensional volume they enclose.

One such technique was the sketching of front and back bed planes onto 3-dimensional line drawings within the Shima Seiki programming interface. As a relatively quick and simple means of constructing a diagrammatic reference, these drawings provided an effective tool for the mapping of knitted surfaces. Further, in applying the mapping to a 3-dimensional volume, the shapings of various operatives were easier to visualise and represent, in comparison with annotations or adaptations to the 2-dimensional compressed programs. The ability to create these diagrams within the same working space, or screen, as the knit program was also beneficial for maintaining programming momentum and ease of reference. Previously, any workings around program development were recorded or processed in a different medium outside of the WholeGarment design system, often disrupting workflow or thought process.

As the research progressed, the concept behind this mapping technique was developed into a series of schematic process diagrams.[82] Fundamental to this technique was the matching of planes within a 3-dimensional geometric form to the parallel needle beds on which they were fabricated, and therefore the 2-dimensional programming grid of their construction space. Based on this principle, an initial graphic was developed showing the step-by-step mapping for the fabrication of a cube. As the operative groupings of cubic geometries emerged, mappings for each operative were also developed.

There are multiple methods for programming 3-dimensional geometries, and there can be multiple construction techniques and/or sequences for producing any single composition. The methods and sequences used

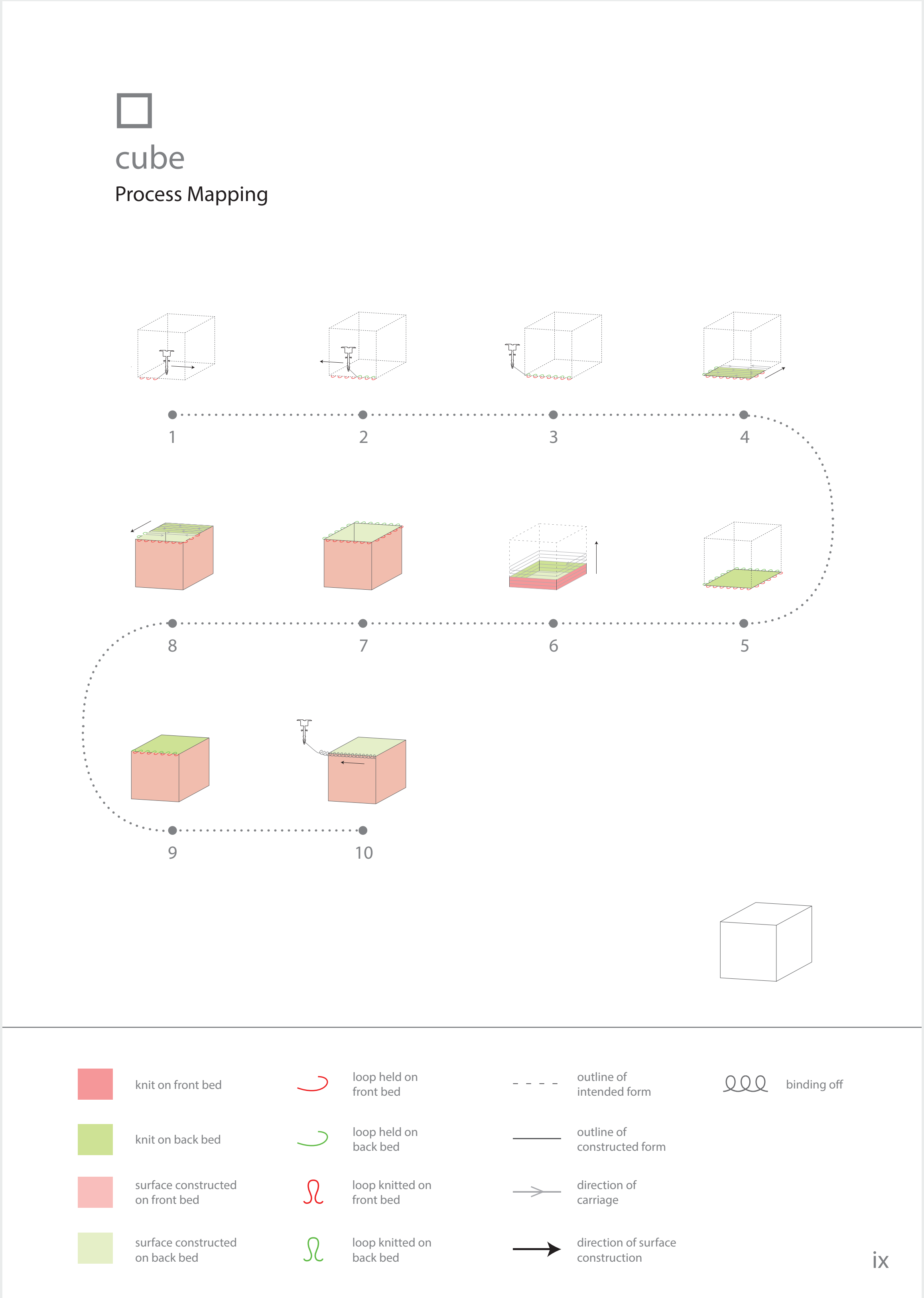


Figure 5.35
+ cube, process mapping diagram, 2018.

in this research emerged directly from the design practice; largely within the systematic investigation of cubic geometries in Part 3 and, therefore, it is these specific processes of form building that are mapped.

While initially intended as an explanatory or instructive tool, the format of the mappings (Figure 5.35) evolved in such a way that the isolation of points of departure in each step in the process supported the consideration and programming of alternative geometries. To explain further, each step in the mapping process corresponds to the fabrication of an additional plane, or a point in the fabrication where loops are held so that another plane can be integrated into the form. Therefore, though the process is mapped in a prescriptive manner, the explicit mapping of held loops highlights the multiple points of departure and subsequent opportunities for further experimentation within each form.

Fabricated Form

Knitted 3-dimensional geometric form

Within the cubic form-building system the photographic image of fabricated form provides the most direct and easily understood visual reference of the geometric form that can result from application of an operative. As for the other elements, for each operative the photographed form corresponds to the other representations within the system, such as compressed program and 3-dimensional line drawings.

An extensive discussion of the function that the fabricated form plays within the research and in the form-building system is provided in Chapter Six, Artefact, as physical form embodying knowledge. As for the physical artefacts discussed there, the photographic image similarly embodies the insights from the practice in an easily interpreted format. In this way, it serves to demonstrate form-building capability and invites engagement from a broad range of practitioners.

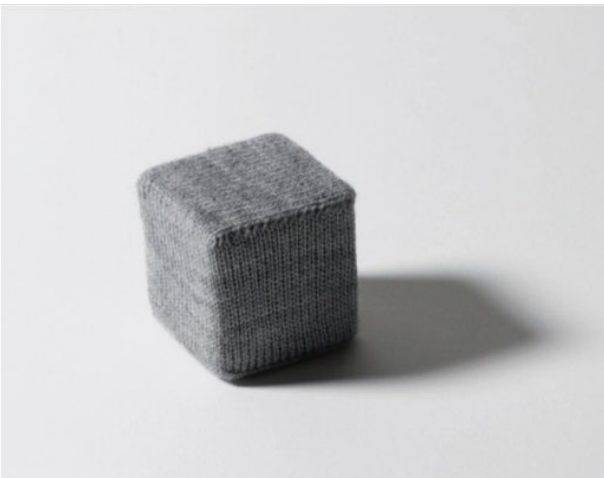


Figure 5.36
+ cube, fabricated and filled form, 2018

Summary

The cubic form-building system presented here is intended as a framework for the ongoing investigation and documentation of 3-dimensional knitted geometries. Multiple modes of representation within this system work in combination to provide a comprehensive overview of fabrication for a specified operative within the WholeGarment environment. However, recognising that the 3-dimensional form-building domain remains largely undefined, the format of the system is such that it provides a template for continued development and extension in what is intended as an evolving system.

These modes, or the operatives and elements within the system, derive directly from the design practice and, as such, represent key findings from the research, ranging from broadly interpretable design concepts to WholeGarment specific technical mappings. Within this format, the findings are intended to be accessible by a wide range of practitioners, both from the knitted textiles field and outside of it. While it is not expected that all practitioners will engage with all aspects within the system, the format is considered to provide practitioners from varying backgrounds insight into the elements within the WholeGarment environment alongside awareness of its fabrication potential. In addition, as discussed further in Chapters Six and Seven, the system provides mechanisms for shared understanding and collaboration, further improving access to the technology's advanced capability.

As the cubic form-building investigation continues in Part 3, the exploration of operatives and development of cubic derivatives are documented within the framework of this cubic form-building system.

62 The incongruities and the insights they revealed are discussed later in this section, in Operatives, and throughout Part 3.

63 In tubular knitting the number of needles being used on front and back beds is always even.

64 For this research it was expected that the practice would yield a comprehensive database of packages and programs for the fabrication of a range of 3-dimensional cubic forms. The experimental nature of the practice and focus on testing of geometries meant I was reluctant to revise compressed programs for forms that had already been fabricated. In pursuing this line of research, I would seek to create an updated library of packages, reducing the number of repeated construction techniques where possible by revising compressed drawings.

65 A shaping construction technique whereby increasing and/or decreasing the length of succeeding knitted courses creates a wedge within a surface.

66 Determination of the unit of measure was based on the size of available foams, the smallest base-volume segment feasible for fabrication and knitting time. With experimentation and iteration being key aspects of the design practice, it was important that forms could be quickly and easily fabricated for evaluation so that the practice could maintain momentum.

67 Also related to this arrangement and impacting on the final measure of the fabricated form is that the cubic geometry contains a row of 'looser stitches.' The join at the intersection of perpendicular planes is not a knitted stitch as such; rather it is the connecting of loops in such a way that a looser row of 'stitches' remains.

68 With a more considered fabrication or in areas such as technical knitting, changes can be made to the sizes of specific stitches or rows of knitted stitches to enable a more accurate form.

69 See Figure 5.33 for further detail on construction techniques utilised in fabrication of cubic geometric forms.

70 Or more specifically, in the case of the compressed drawing, no change to the packages used or the sequence they were used in.

71 While an effective solution in this instance, there are numerous ways an alternative opening could have been achieved. For example, in the same orientation as the original cube program, one could c-knit an opening into the tubular portion of the form. Further openings were explored as the practice progressed. These are outlined in the Openings and Closures section.

72 Such as in Part 3, Compositions

73 The open edges of knitted cloth in c-knit naturally roll. With bound edges, though the cloth rolls, the act of binding the knitted stitches provides additional structure within the cloth, which in turn provides stability for the hand-stitched finish.

74 Specifically, two ends of Nm 36/2.

75 This is another area where the use of CAD technologies would be of benefit, as the ability to model the geometry within the software would allow for the required metrics to be easily determined.

76 Testing and demonstrating a range of technical yarns in cubic geometries would be a valuable avenue for further research.

77 See Chapter Three, Alternative Approaches to Form Building, for further detail and format of this system.

78 In referencing this system as a version, the research acknowledges that the system is not considered to be a definitive framework for the fabrication of 3-dimensional knitted geometries. Rather, it offers an initial approach that is intended to be further developed and populated, and which could be utilised alongside other form-building systems to provide a more comprehensive background to 3-dimensional form-building within the WholeGarment environment. This aspect of the research is discussed further in Chapter's Six and Seven.

79 It is not that the spatial operatives are not relevant – even in architecture, one would consider the skin of a volume – rather the terms are confusing in the exploration of an additive fabrication space.

80 With further consideration during and after the exhibition, some of the language and notations were revised. These revisions are outlined in Chapter Six, Operatives, Attributes and the Cubic Form-building Domain.

81 A package is a coded programming component whereby each line of code represents a group of knitting instructions. These packages of code are used to create compressed patterns.

82 The sketches from which the process mappings derive are constructed in Shima Seiki's programming interface. However, the mappings themselves have been developed in Adobe Illustrator.

83 Note that c. in Figure 5.38 results from a prism integrated above and below the tubular knit. With reference to the form-building journey in Chapter Six, this is considered as three integrations, whereby a wedge is integrated with a tubular component, which is then integrated with another wedge.

Chapter Five

Part 3 - INVESTIGATION OF KNITTED CUBIC FORM-BUILDING

Systematic investigation of feasibility, parameters and constraints of knitted cubic geometric forms guided by operative form-building actions

Process mapping sketches with programming interface of representing what was happening visually

Incongruity between spatial operatives and additive knitted textile constructon

Orientation and sequence matter

GitHub as a program version and documentation tool

+ wedge	Expand through bias knit planes
+ ledge	Filling holes and integrating folds Front bed bias knit planes *
+ swell & taper	Widening and narrowing through tubular knit, within a surface or at its edges
+ hinge	Joins or hinges **
+ spiral	Racking *** Cross bed stitch movements
Compositions	Merge and integrate

Figure 5.37

Practice Framework, Part 3.

Part 3

Investigation of Knitted Cubic Form-building

In this section (Figure 5.37) the practice investigates the feasibility, parameters and constraints of a range of cubic geometries, each of which begins its development from one of the base volumes established in the previous section (Part 2, Foundation for a Form-building System). While the investigation was initially prompted by spatial operatives from Di Mari and Yoo's*Operative Design: A Catalogue of Spatial Verbs* (2018), the research path soon diverged as technological insights informed the consideration and evaluation of alternative groupings and further derivatives.

In documenting the investigation, this section follows the path of discovery, addressing each operative grouping as it emerged, in its endeavour to reveal form-building processes. For each operative the key findings are presented first, within the format of the cubic form-building system described in Part 2, presenting a contextual framing. Following this, the text turns to documenting the emergence of the operative and its subsequent population with derivative geometries. At times the practice was led in unexpected directions, sometimes allowing for earlier unresolved geometries to be revisited and resolved. Though systematic in its overarching process, elements of trial and error, movement back and forth between fabrication categories, and deferred testing appear throughout.

As in Parts 1 and 2, technical findings and conceptual insights are addressed as they arise, revealing both affordances and limitations of WholeGarment technological capability through the construction of 3-dimensional cubic geometries. The Part is illustrated primarily with images and workings from the Shima Seiki design system. Alongside this, the fabricated artefacts from this phase of the practice are documented in Appendix B, providing a comprehensive introduction to, and demonstration of, the vast potential within the knit form-building domain.

Operative

+ wedge

Attributes

- triangular prism which can be integrated within the tubular knit or bias knit planes of cuboid fabrication

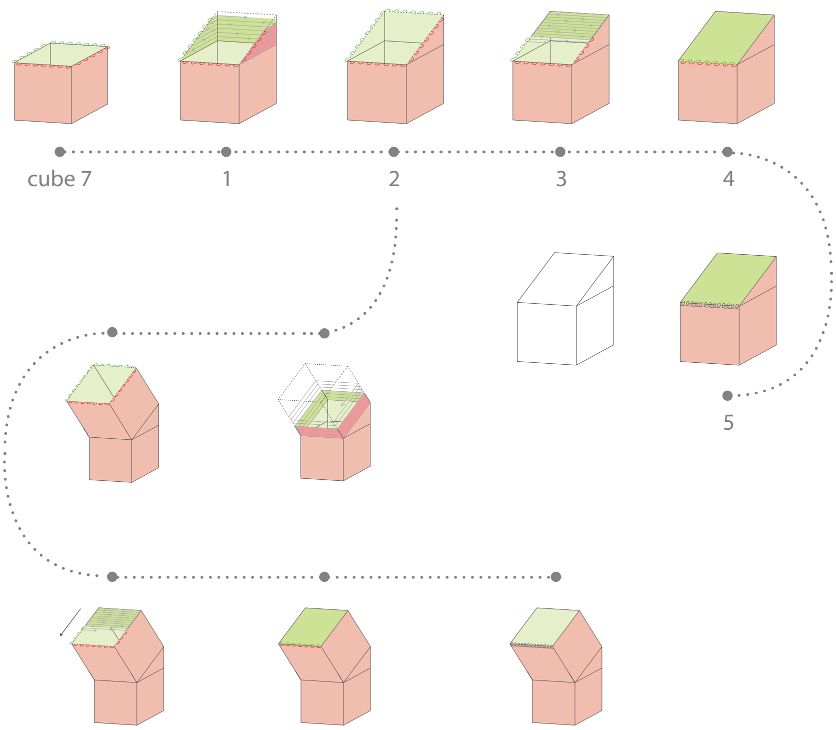
Compressed Program

Construction Notes

- flechage or short-row in tubular knitting
- knitted loops are added through additional courses of knitting
- can expand through bias knitting

Fabricated Form

Process Mapping



- knit on front bed
- knit on back bed
- surface constructed on front bed
- surface constructed on back bed
- loop held on front bed
- loop held on back bed
- loop knitted on front bed
- loop knitted on back bed
- outline of intended form
- outline of constructed form
- direction of carriage
- direction of surface construction
- binding off

xii

Figure 5.38
+ wedge, cubic form-building system, 2019.

+ wedge

The operative Wedge (Figure 5.38) emerged from an exploration of the first spatial operative in the *Operative Design* text (Di Mari & Yoo, 2018) – Expand (Figure 5.39). The first few derivatives attempted were relatively straightforward, drawing from programming components used in the fabrication of base volumes. However, the mapping of angular planes onto a cubic form, and the varied orientations of the wedges in additional derivatives, proved more complex, prompting a period of experimental programming and fabrication.

Programming of the geometries is initiated by selecting a cuboid base as an entry point. Interpreting the intended form through an additive knit perspective, it can be seen that the first series of wedges can be assembled in such a way that a triangular prism is integrated above or below the selected base (see A, B and C in Figure 5.40[83]). In this format, the short-row knitting technique applied in the 3/8 Base Segment can be utilised to 'expand' one end of the cuboid to create a wedge effect. Derivatives of this composition emerge through altering the dimensions of the wedge, altering the placement of the wedge, or both.

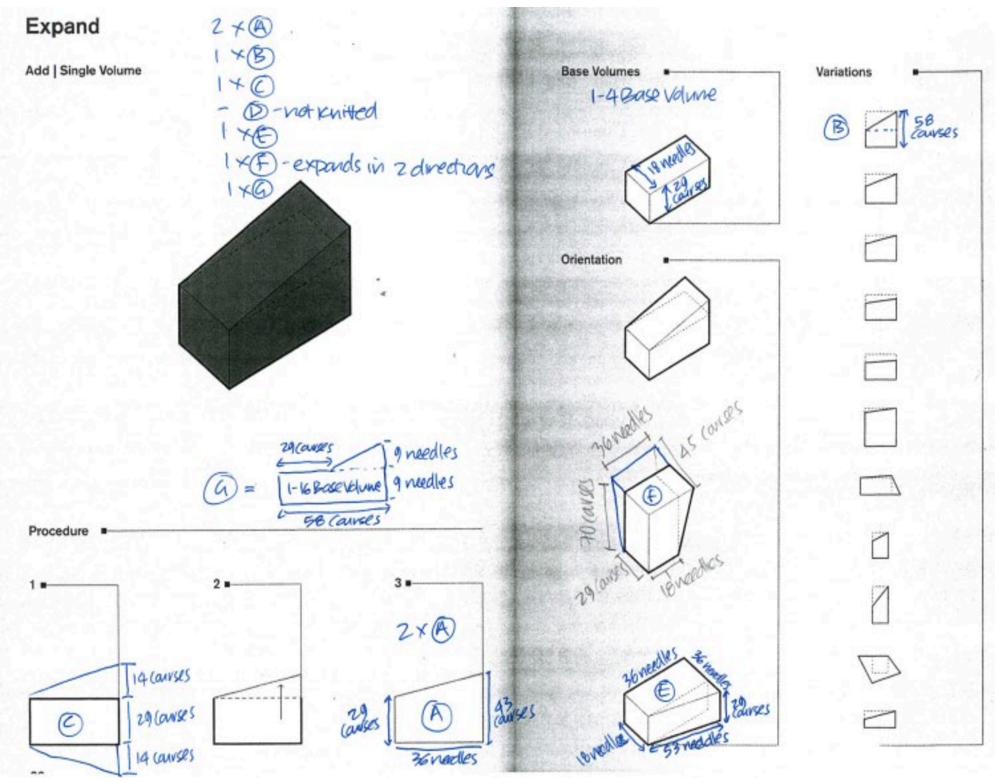


Figure 5.39
Expand, annotated, 2018.

The next series was prompted by consideration for whether the geometry could be expanded in more than one direction. In the surface fabrication of a cuboid, this translates to whether the top and bottom surfaces of the form can be expanded; essentially accommodating a cuboid base with a triangular wedge added to the side of a tubular-knit segment, rather than on top or below.[84] Therefore, the practice turned to the bias-knit fabrication of the top and bottom cuboid planes; a considerably more complex construction than the tubular-knit segments expanded in the first series.

A period of experimentation followed as I attempted to resolve a balance between picking up stitches to increase the width of the plane, knitting on the bias, and working within the slide format[85] and rows of repeat of the bias-knitting package. Experimentation was primarily within the programming module of the software (Figure 5.41) as the effectiveness of package adjustments could be evaluated in developed programs without the need for fabrication.

Though I had a sense of the intended knit fabrication, the possibility of programming this construction in combination with the slide function within a compressed drawing became an unknown. With limited experience of manipulating the slide function, the required sequence and format proved complex, with numerous iterations required before arriving at an effective balance. As shown in Figure 5.42, two programs (D and E) were developed, offering different proportions in the rate of expansion.

In this instance, though it may have been quicker to program the desired construction in a developed program, I was focused on achieving an effective result through compressed drawing and program packages. One of the research aims of this project relates to the possibility of a 3-dimensional knit-fabrication library. Programmed components in such a library could be selected and integrated as required to develop a range of knit geometries. In this objective the development of packages as representations of specific knit techniques is core to the research.

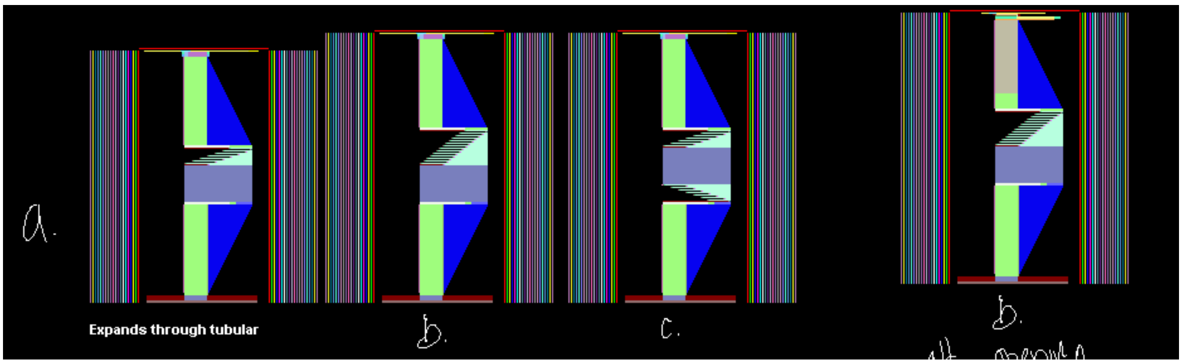


Figure 5.40

+ wedge, compressed knit programs, 2018.

Derivatives A and B have prisms integrated above or below the tubular knit.

Derivative C has prisms integrated above and below the tubular knit. With reference to the form-building journey in Chapter Six, this is considered as three integrations, whereby a wedge is integrated with a tubular component, which is then integrated with another wedge.

Derivative B alt. opening has an alternative opening along the length of bias knitting rather than on the last row of the last bias-knit plane.

With the proven capability to integrate wedges in multiple directions, a further geometric form was fabricated in which both orientations of the triangular wedge were integrated into a single cuboid base; one above the tubular component and one within the bias knit, as seen in derivative F, Figure 5.42.

Significantly, the incongruity of the spatial operatives and knit fabrication was already evident at this early stage. To explain further, in the text (Di Mari & Yoo, 2018) *Expand* results from an additive process, while *Shear* results from a subtractive process. However, both operatives result in the same geometric form. In the WholeGarment environment, the operatives would follow the same construction techniques and sequence. For this reason, Shear was not addressed in the investigation.

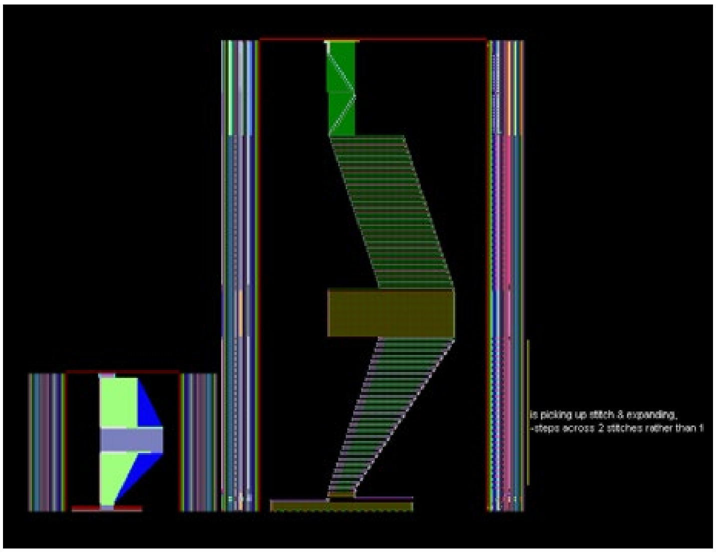


Figure 5.41
+ wedge, compressed and developed knit program for testing expansion through a bias-knit plane, 2018.

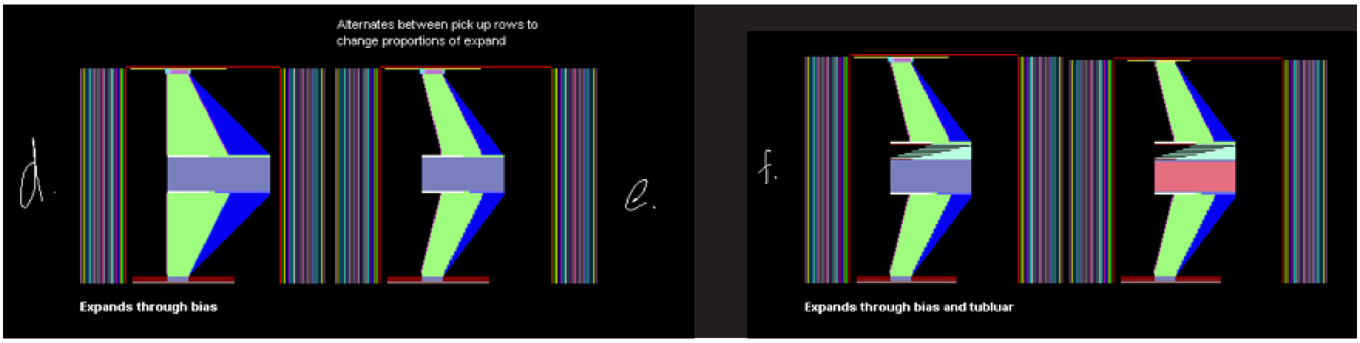


Figure 5.42
+ wedge, derivatives D, E and F, 2018.

Extensions of + wedge

The following geometries were established later in the practice and are categorised under Compositions. However, as direct extensions of an initialised Wedge they are addressed in this section.

The first geometric form integrates a Wedge within the tubular segment, or sides, of a cuboid to create a bend within the form (Figure 5.43). More specifically with regards to construction, before closing a wedge that sits on top of a cuboid base, an additional segment of tubular knitting is fabricated above. The configuration of multiple bends in a given orientation and sequence allows for a range of stepped and zig-zagged patterns within cuboid geometries (Figure 5.44).

In this next set of geometries, a wedge is integrated at the start and finish of the tubular knit segment to create a skewed effect within the form (Figure 5.45). That is, the cuboid is fabricated so that its top and bottom surfaces (bias-knit planes) sit at a non-perpendicular angle to its height (tubular-knit segment). In these samples, the skew effect was not fully resolved. I understand this is in part due to the combination of a small sample size and the directional pull created by the sharp wedge dimensions. Further, the placement of a wedge immediately before or after bias-knit planes adds increased tension at the edges where the wedge intersects with a tubular-knit segment. I believe both of these aspects could be addressed through further experimentation with the technical attributes of the fabrication, such as stitch sizes and takedown values.

+ ledge

The + ledge component (Figure 5.46) was investigated early in the practice, though the complexity of some elements led to some derivatives being deferred, and the operative being revisited a number of times. As fabrication understanding improved as the practice progressed, the full extent of fabrication capability was realised. The fabrication of perpendicular planes, the defining attribute of this category, has been addressed in previous phases of the research.[86] However, it was the second action in the text – *Extrude* – that prompted a more comprehensive exploration of this attribute and its potential application. Though I was unaware of its significance at the time, the capability to construct right-angle planes on any side of a cuboid, which emerged in the exploration of this grouping, is a critical finding, exposing extensive potential in the fabrication of 3-dimensional cubic geometries.

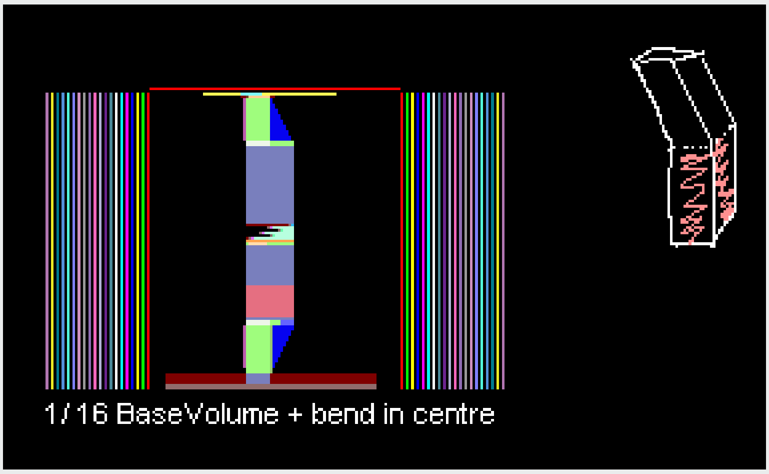


Figure 5.43
+ wedge, extended with additional cuboid above wedge, 2018.

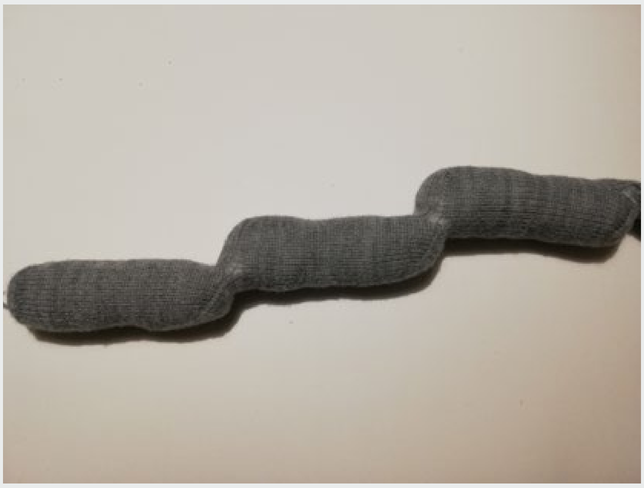


Figure 5.44
+ wedge, multiple bends, soft-filled sample, work in progress for exhibition, 2018.

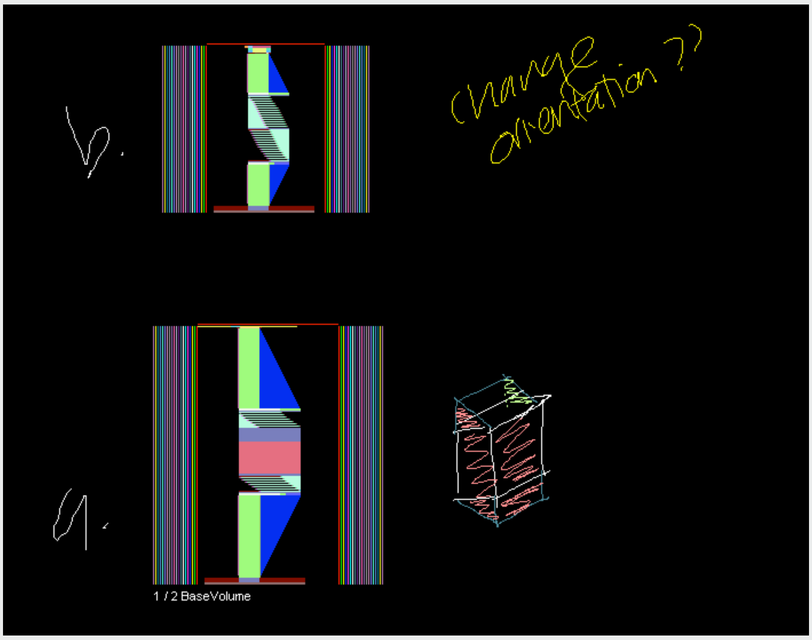


Figure 5.45
+ wedge, extended with wedges either end of a cuboid, 2018.

Operative

+ ledge

Attributes

- a perpendicular plane
- can be used to extend or shorten cubic geometries

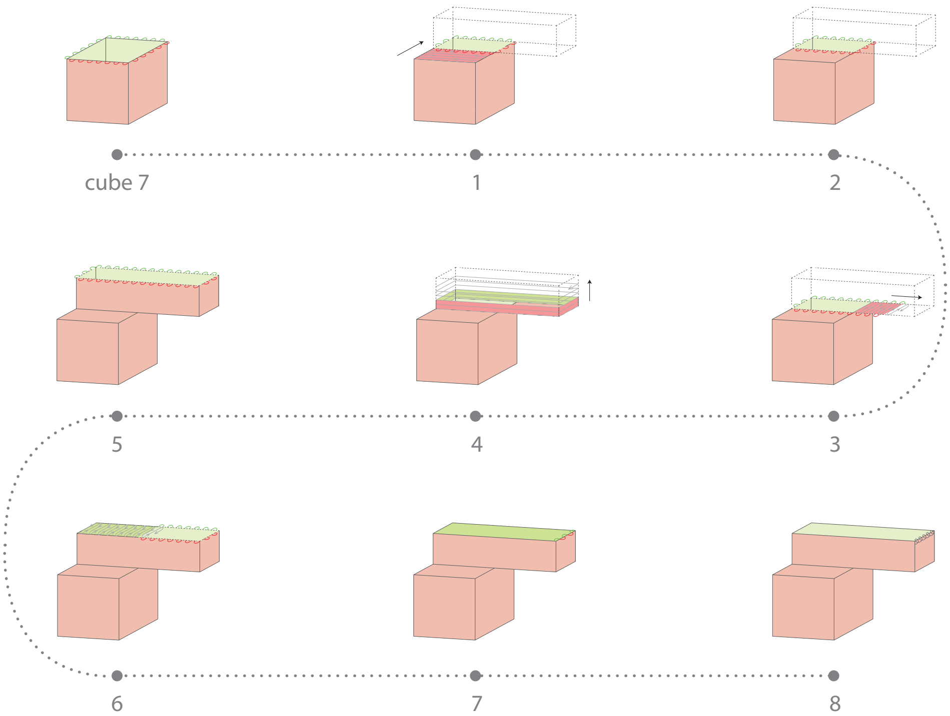
Compressed Program

Construction Notes

- bias knit
- on front or back bed
- can be constructed with bias from left to right or vice versa

Fabricated Form

Process Mapping



- knit on front bed
- knit on back bed
- surface constructed on front bed
- surface constructed on back bed
- loop held on front bed
- loop held on back bed
- loop knitted on front bed
- loop knitted on back bed
- outline of intended form
- outline of constructed form
- direction of carriage
- direction of surface construction
- binding off

xiv

Figure 5.46
+ ledge, cubic form-building system, 2019.

Derivative A, shown in Figure 5.47, was attempted first. After orienting the form so that it resembled a layering of cuboids, it was apparent that some components of the geometry had been previously proven. Specifically, I knew that it was possible to construct a cube so that its opening was within the last fabricated plane rather than at one of its edges.[87] Further, the capability to layer cubes of equal width or length was also a known possibility.[88]

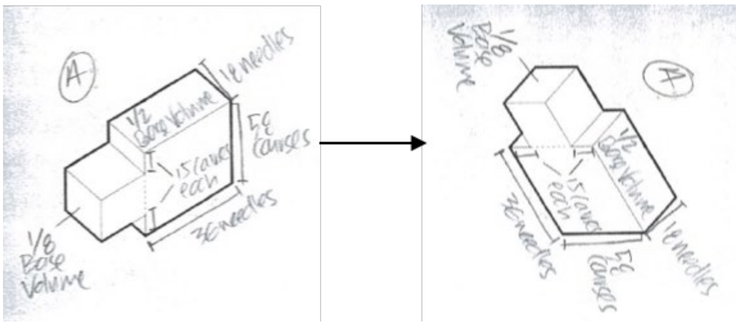


Figure 5.47
Extrude (+ ledge, derivative A) orientations, 2018.

The new element in this form was the mapping of one ‘open cube’ on top of another. In previous layering, the cubes had been stacked on top of one another as ‘closed’ forms, such as for the artefacts in Part 1, Computational Literacy. In determining the programming for this new element, accurate mapping of planes and needle beds was essential. As the construction of planes was not yet grounded in an intuitive understanding, and with no established mechanism for evaluating this mapping, several iterations were required to ensure planes were closed and extended in the correct alignment and that no stitches were dropped in the process (Figure 5.48).

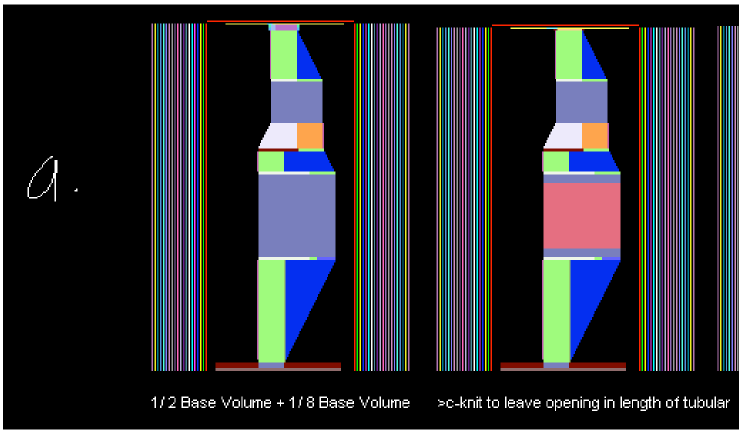


Figure 5.48
+ledge, derivative A, 2018.

The programming of Derivative B (Figure 5.49) and the mapping of its planes proved more problematic, with early iterations proving inaccurate. This motivated a return to the concept of mapping fabricated planes to a 3-dimensional line drawing as I endeavoured to reconcile form, planes and the 2-dimensional knit program. Mapping of planes in this way was useful in understanding how to orient volumes in such a way that the variable dimensions when rotated could be determined, as shown in Figure 5.22, with the 1/16 Base Segment.

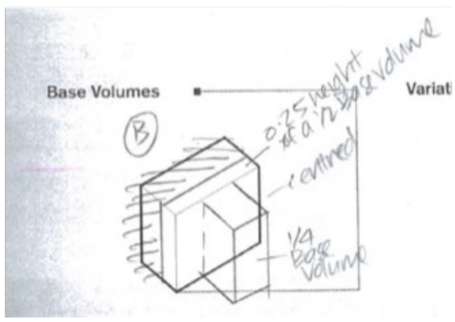


Figure 5.49
Extrude (+ ledge, derivative B), 2018.

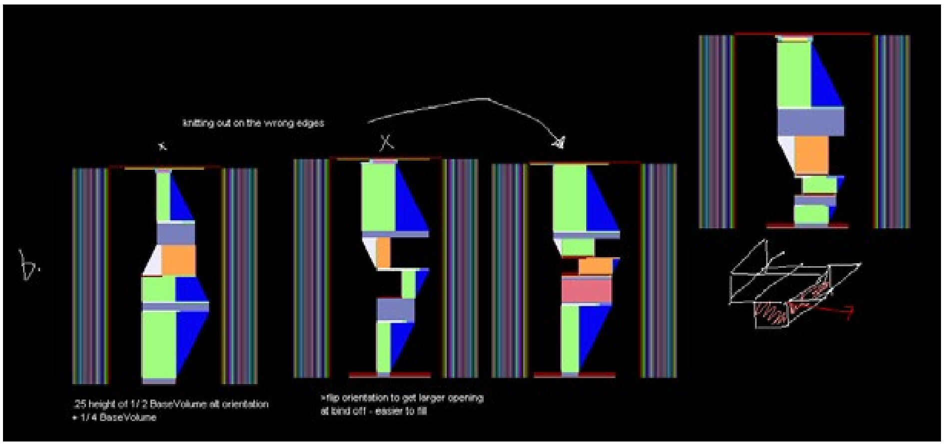


Figure 5.50
+ ledge, mapping derivative B., 2018.

In Figure 5.50, though not all of the form is shaded, the area that is shaded is sufficient to indicate which planes of the geometric form were fabricated on front and back beds, where loops were held and, subsequently, the positioning of extended perpendicular planes. Derivative C. (Figure 5.51) was programmed and fabricated following a similar process as for Derivative B.

The sequence of construction was a critical consideration in these forms. Numerous stitches were held while the yarn needed to be ‘moved’[89] to the required location for fabrication of additional planes. Errors in the order of construction resulted in dropped stitches or long floats, or yarn crossing the needle bed, which was likely to close the geometric form through an unintentional stitching of the sides together. The significance of sequence in constructing complex forms was discussed previously in Part 1, Knit as Pliable Topological Surface.

It is Derivative D (Figure 5.52) in this series that required significant experimentation, both in programming and fabrication. Development of this form was dependent on a comprehensive understanding of bias knitting and directional planes; a technique that I was only starting to grasp.

In this form, the tubular component of a cuboid base needed to be ‘closed’ from all four sides before the smaller cube could be integrated above. Mapping these four areas of fabrication on a 2-dimensional drawing, or the parallel needle beds of its construction, was particularly challenging. An attempt to draw the planes onto a 3-dimensional sketch in Figure 5.53 shows the areas of uncertainty with regard to how the ‘grey areas’ would be formed. Based on the construction concept of earlier derivatives I could see how to close the geometric form from opposing ends. However, closing the form from the other two edges was an unknown.

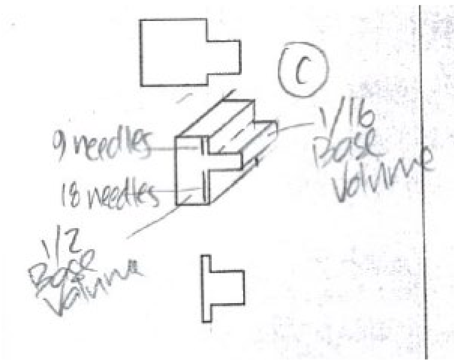


Figure 5.51
Extrude (+ ledge, derivative C), 2018.

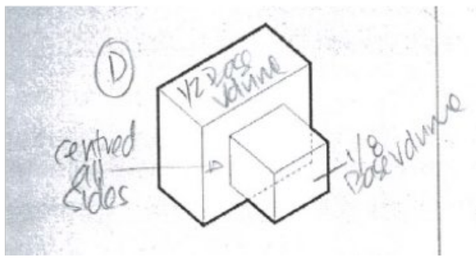


Figure 5.52
Extrude (+ ledge, derivative D), 2018.

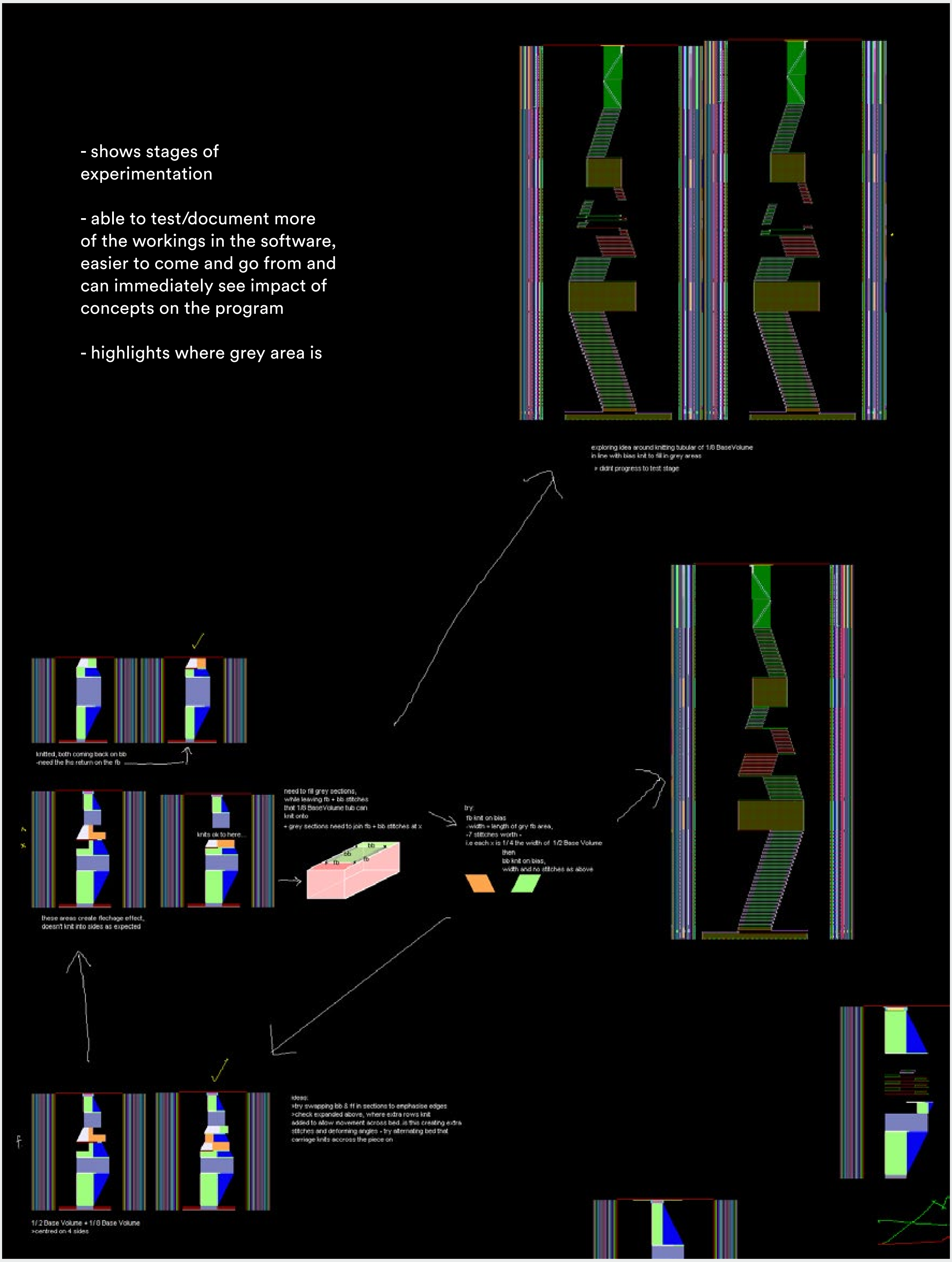


Figure 5.53
+ ledge, development of derivative D, 2018.

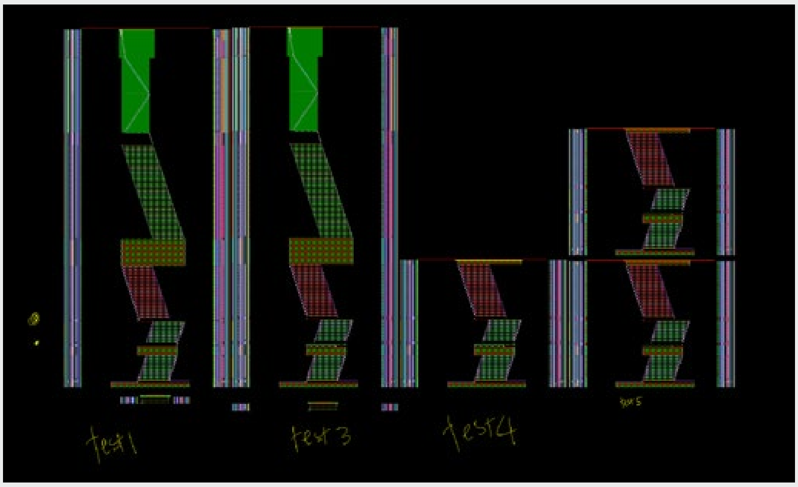


Figure 5.54
+ ledge, testing in developed program, 2018.

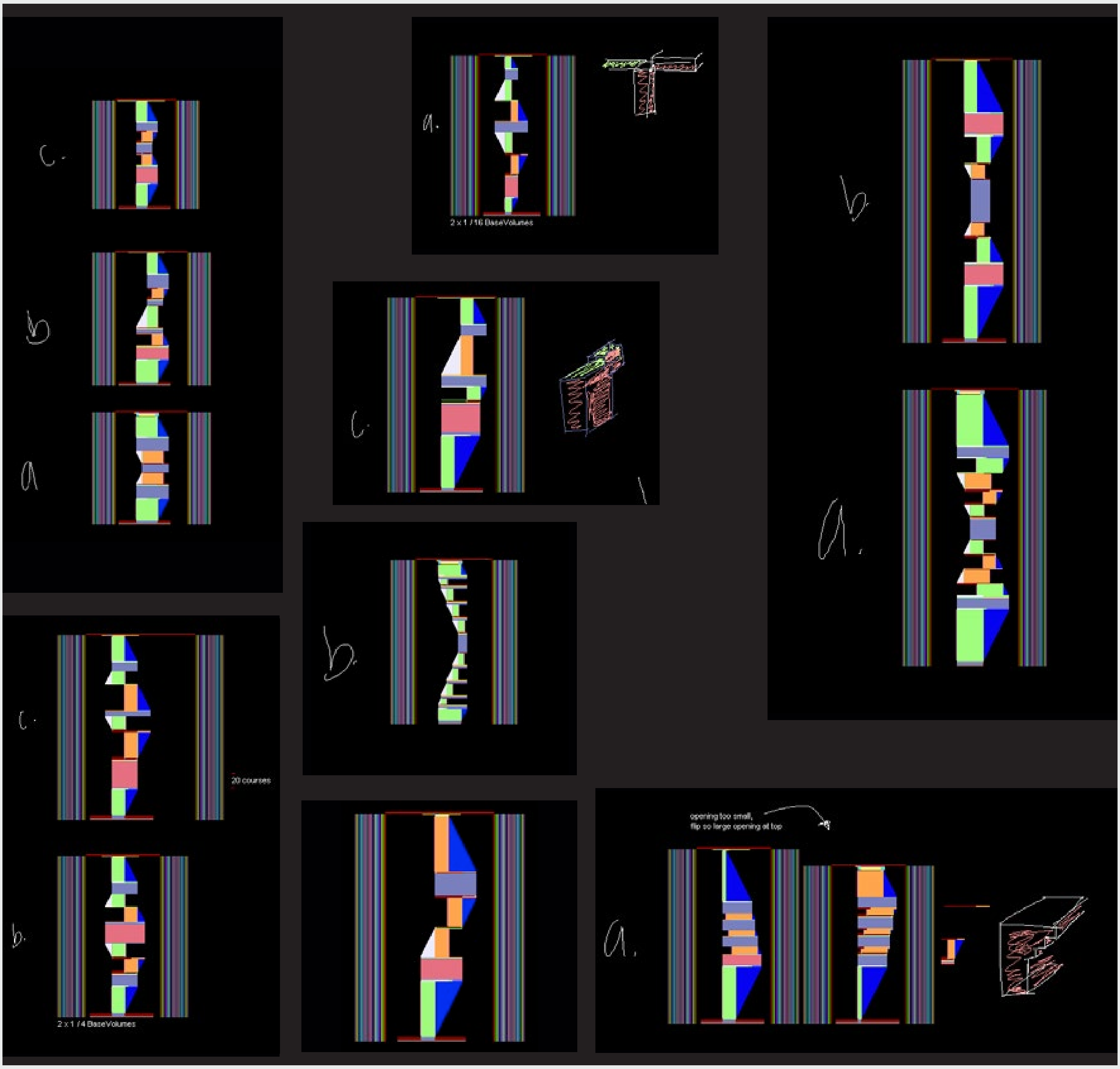


Figure 5.55
+ ledge, further derivatives, 2018.

Various construction techniques were trialed, with the geometric form being left unresolved, and revisited a number of times. Early iterations were directed towards partially extending the existing planes in order to fill the grey area. With limited understanding of directional planes, it was necessary to fabricate forms where possible to evaluate effectiveness. In this instance, composing a program to the level of completeness required for development and fabrication was time consuming. As such, it was more effective to trial concepts in a previously developed and tested program, needle by needle (Figure 5.54). In this way, small changes could be programmed and tested on an existing program before packages were composed. This was also beneficial in that fabrication concepts could be tested before being directly integrated into larger samples.

This period of initial experimentation, though ineffective in its realisation of the intended geometric form, was beneficial in providing further insight into the mapping of planes and needle beds. Alongside this was an ongoing theoretical evaluation of various construction concepts. The eventual solution[90] that emerged for this geometric form was based on insights from the experimentation in Part 1, Extending Computational Literacy: A New Perspective of the Knitted Cube, regarding the capability to knit bias planes in different directions using the front needle bed. Though this experimentation had revealed that bias planes could be knitted in different directions, I had not explored the construction in enough depth at this point to understand its application and parameters.

‘Filling’ Holes and Integrating Folds

Two additional programming components arose from the fabrication of these geometries. Though neither impacts on the form-building aspect of knit construction, they are initial endeavours to address some of the technical refinements that could be made. The first emerged from endeavours to fill the ‘hole’ that was created where a cube was closed by adjacent planes knitted in different directions. Experimentation with knitting directions, sequence of plane fabrication and stitch qualities were ineffective in reducing the visual impact of this hole. At this stage a cable-stitch effect has been used for this purpose, but further experimentation is required to develop a more effective solution.

The second component relates to the notion of folds in the cloth. A plane fabricated at right angles can be folded in or out, depending on its intended geometric form. Based on factors such as the direction of stitches and any patterning in the fabrication, the planes will naturally fall to one side rather than the other. In order to emphasise the intended direction, I experimented with varied combinations of miss, plain and purl stitches in the rows fabricated at the intersection of perpendicular planes. A miss-stitch combination was considered most effective, with four packages developed to reinforce folds in either direction, and on the front- or back-bed fabrications.

Populating + ledge

The insight gained from the directional knitting of bias planes opened up a vast sphere of possibility in the fabrication of cuboid geometries. In the text there were many additional operatives that could be fabricated by applying the technological capability to knit ledges. As the research shifted to the programming and fabrication of further geometries, inspired by both the spatial operatives and self-generated ideas, a period of rapid fabrication transpired through which a substantial collection of geometries was produced. With an increased level of understanding in regard to directional knitting of bias planes, and a diagrammatic mechanism for representing the positioning and direction of these planes, the programming of further + ledge derivatives (Figure 5.55) was significantly faster process, rarely requiring more than one iteration to develop and fabricate successful outcomes.

A number of additional packages were formulated when populating this category, largely due to the differing directions and sequences of construction that were now being applied in the fabrication of geometries. For example, given the possibility of four different directions in the last plane of a geometric form (front- and back-bed bias-knit planes, from left to right and right to left) additional bind-off packages were required to address these different directions in the last course of knitting for closing forms.

For example, spatial operatives *Nest* and *Offset* (Figure 5.56) both contain perpendicular planes. However, it does not appear feasible for these geometries to be constructed, as all or part of the form is reliant on four layers being fabricated simultaneously.

A possible solution is offered by the findings of Part 1, Knit as Pliable Topological Surface. In that section, it was demonstrated that with 1/4 gauge construction and the introduction of additional carriers, four layers of cloth could be fabricated as two independent tubes. Time constraints restricted further investigation into the application of this principle on these geometries.

Though taking on a different format from the operatives *Nest* and *Offset*, *Extract* and *Interlock* (Figure 5.57) were also considered to require a four-layer fabrication somewhere within their form. Though I have not unpacked these geometries extensively to consider their components and sequence, it appears that a 1/4 gauge system may also be of benefit in these cases. Again, this research remains unresolved due to time constraints in this study.

+ ledge as Further Research

In the Operative Design text there are also a number of geometries whose composition indicates that the ledge fabrication capability could be used in their production. However, the numerous layers within their forms mean they remain unrealised.

For example, spatial operatives Nest and Offset (Figure 5.56) both contain perpendicular planes. However, it does not appear feasible for these geometries to be constructed, as all or part of the form is reliant on four layers being fabricated simultaneously.

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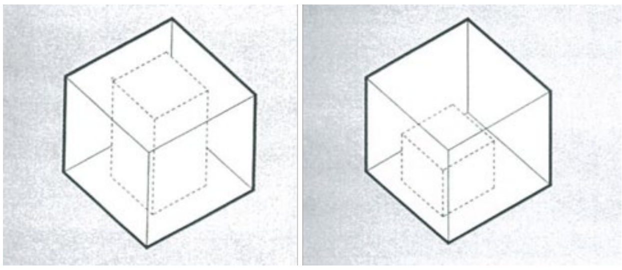


Figure 5.56
Offset, Nest,. Di Mari and Yoo (2018).

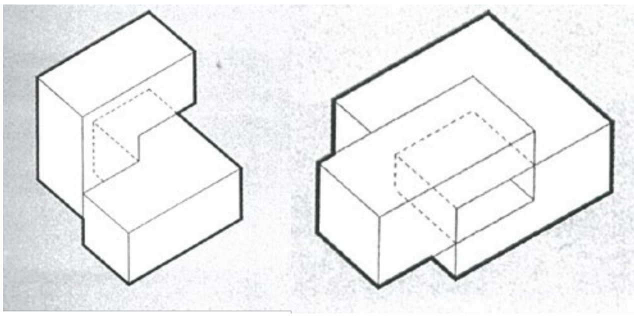


Figure 5.57
Interlock, Extract, Di Mari and Yoo (2018).

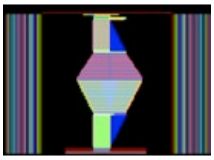
Operative

+ swell & taper

Attributes

- a triangular prism which can be integrated within the surfaces of tubular knit rather than at its edge
- primarily utilises inside widening and narrowing to ncrease or reduce the width of a plane

Compressed Program

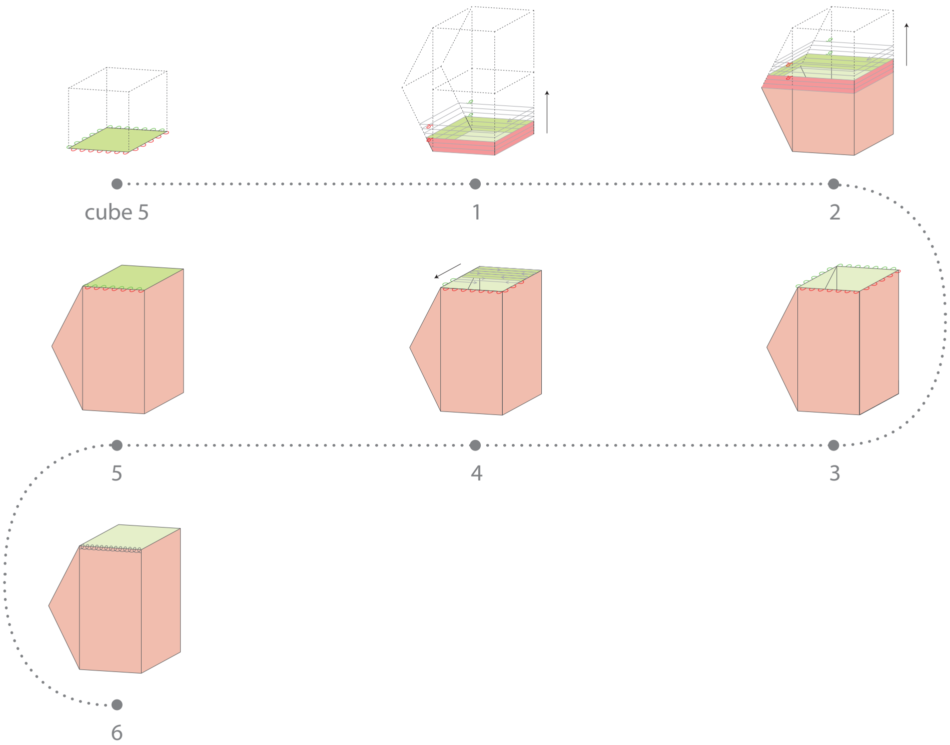


Construction Notes

- widening or narrowing through tubular knit component
- can be within a knitted surface or at its edges (inside or outside)
- knitted loops are added or removed within a course of knitting
- flechage

Fabricated Form

Process Mapping



knit on front bed

knit on back bed

surface constructed on front bed

surface constructed on back bed

loop held on front bed

loop held on back bed

loop knitted on front bed

loop knitted on back bed

outline of intended form

outline of constructed form

direction of carriage

direction of surface construction

binding off

xvi

Figure 5.58

+ swell & taper, cubic form-building system, 2019.

+ swell & taper

The category + swell & taper (Figure 5.58), prompted by the exploration of the spatial operative *Inflate*, was considered reasonably early in the practice but remains the least resolved, primarily due to my limited experience or application with narrowing and widening construction techniques.

The first two derivatives (Figure's 5.59 and 5.60) utilised flechage knitting techniques to create triangular prisms above and below the 1/4 segment base. In A, the triangular prism is oriented so that the planes between triangular ends of the prism run along the length of the cuboid. In B the planes run across the width of the cuboid.

Despite these geometries using the same construction techniques, a change in the orientation of the triangular prism, and the subsequent change in the positioning of the flechage components, leads to an alternative sequence of programming shown in Figure 5.61. In these samples the sequence of construction is further complicated by the additional courses of fabrication before and after flechage components. Though courses are not precisely even between front and back beds, or the left and right of the geometric form, attempts were made to match these as much as possible. In samples of the size being produced for this research, an extra course visibly affects the symmetry of the form.

The third derivative in this series, which inflated on all sides (Figure 5.62) was considerably more convoluted in its journey to fabrication. Building on the triangular prisms that I knew to be possible from the first two derivatives, I initially tried to map prisms onto a cuboid and determine how to fill in the 'gap' between prisms (shaded blue in Figure 5.63). Without any clear path forward, fabrication of the form was deferred as I continued to explore other geometries.

Though the connection was not made at the time, the next geometric form explored from the spatial operative branch generated an alternative perspective to the widening of cuboid forms, and it is this concept that was used on this form when it was revisited later in this section.

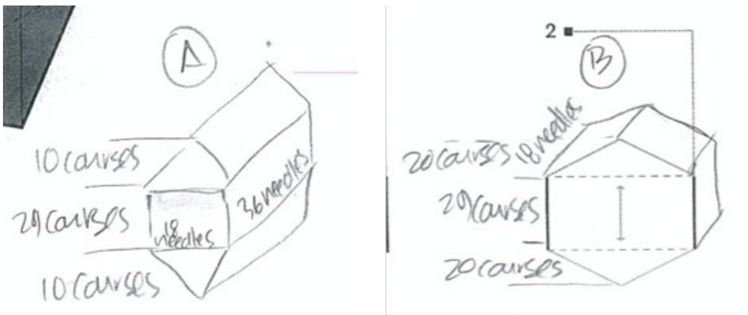


Figure 5.59
Inflate (+ swell and taper, derivatives A and B), 2018.

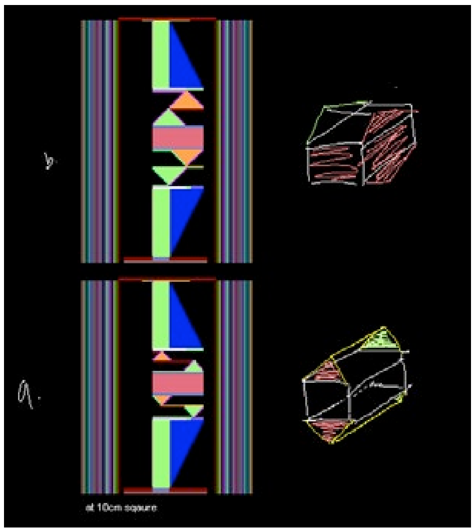


Figure 5.60
+ swell & taper, derivatives A and B, 2018.

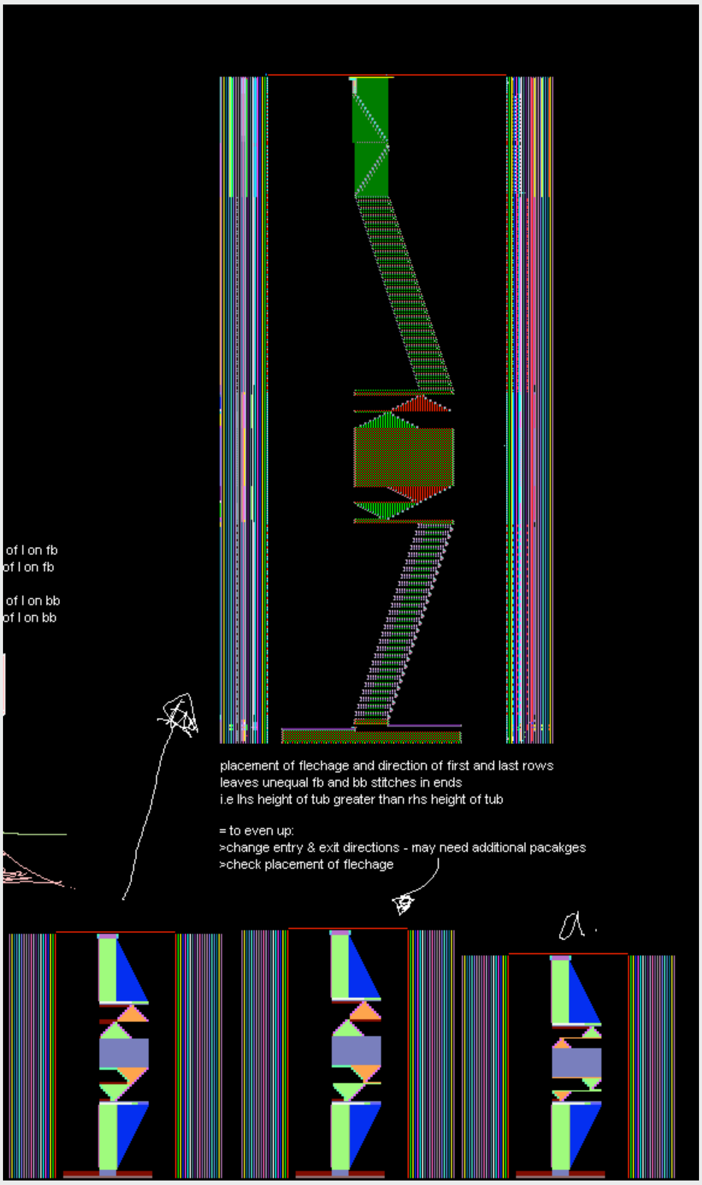


Figure 5.61
+ swell & taper, alternative sequence of fabrication, 2018.

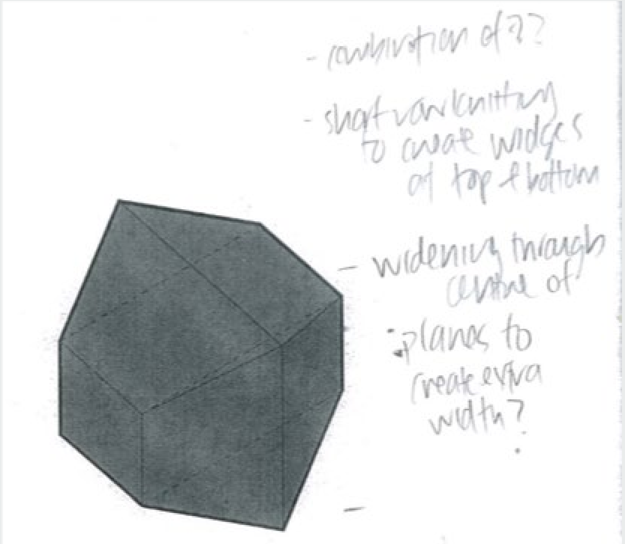


Figure 5.62
Inflate (+ swell and taper, derivative C), 2018.

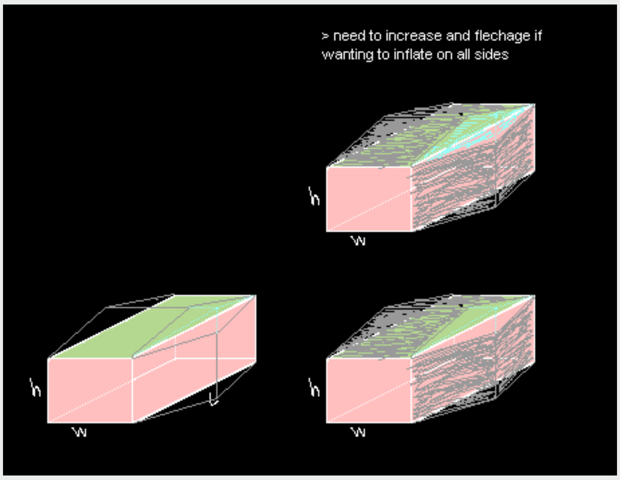


Figure 5.63
+ swell & taper, derivative C, 2018.

Additional Carriers and Integration of Incongruous Surface Areas

Consideration of the spatial operative branch introduced a number of new complexities and components to the fabrication of 3-dimensional geometries. Initially, this geometric form seemed easily realised. The 1/16 Base Segments on which the form is composed were proven components. Furthermore, the concept of knitting adjacent tubular forms was assumed proven. More specifically, the capability to knit adjacent tubular forms using multiple carriers is the construct on which WholeGarment technology relies in its production of seamless knitwear. Conceptually, this was interpreted as the ability to knit cuboids adjacent to each other.

However, it was in the integration of these cuboid forms that its complexity emerged; a concept that was not comprehensively resolved in this research. More specifically, when considering the fabrication of surfaces, it is evident that the knitted edges of the surface bounding a single 1/16 segment cannot accommodate the knitted edges of surfaces bounding two additional 1/16 segments. In order for two cuboids to be integrated into a single cuboid base, stitches or planes need to be introduced in such a way that, at the point of integration, there are sufficient knitted loops for the two additional 'branches' to build upon.

Initial thoughts around reconciling this integration were to introduce an independent plane between the layers of the base cuboid, which, in sitting between the layers, would not be seen once the form was closed. At the point of integration these additional knitted loops could then be introduced into the main body of the cuboid, and rotated to the correct orientation, to accommodate the additional edges as required (Figure 5.64). Working through this concept, I soon realised that an extensive degree of programming was required to test this concept. This was further complicated by a lack of proficiency in my programming knowledge around some of the construction techniques required, such as racking and rotation. For this reason, although it is believed that this concept may have some merit, investigation was deferred.

The concept that was pursued was an adaptation of the original *branch* form in which the base segment was gradually widened in order to increase the available stitches for the branches to be integrated into it (Figure 5.65). In principle, this is

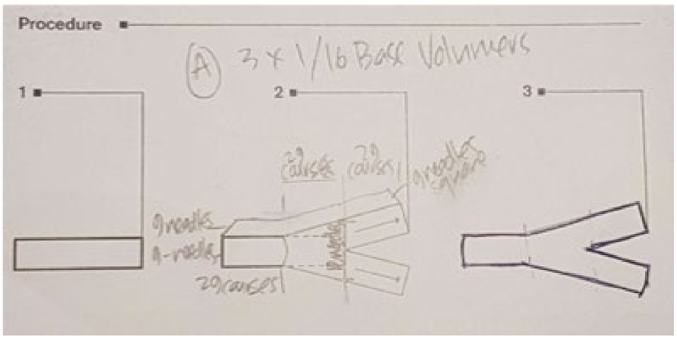


Figure 5.64
Branch (+ swell & taper, composition), 2018.

similar to the idea of seamless knitwear production, where the sleeves and body are integrated into a single form above the armholes. However, the form differs from the garment in its intended cubic 3-dimensionality, and it is in this aspect that the unresolved complexity in the integration of branches arises. The following outlines the development and constraints of this concept in more detail.

As opposed to the triangular prisms that were constructed using a flechage technique in the earlier derivatives (Figure 5.60), the widening in this form retains its cubic geometry. In order to retain the length of the form and only widen across the width, an inside widening technique was used. Inside widening allows for additional stitches to be picked up within a course of knitting rather than at the end of the course; or in 3-dimensional geometries, extra stitches are added within the surface of a plane rather than at its edges. Though the surface dimensions are consistent in both cases, the techniques give a different visual aesthetic and create differing stitch lines within the fabrication process as knitted stitches are pulled in different directions (Figure 5.66).

There are technical reasons[91] in addition to the aesthetic appeal for choosing one technique over the other. In the fabrication of 3-dimensional geometries it is the positioning of the additional stitches and the directional forces this creates within the cloth that are of most interest. As seen in Figure 5.65, it took numerous iterations, both in programming and fabrication, to develop this concept into a form. Aspects such as orientation, mirroring of planes, the positioning of additional stitches and the resulting stitch lines were all factors under consideration throughout this process.

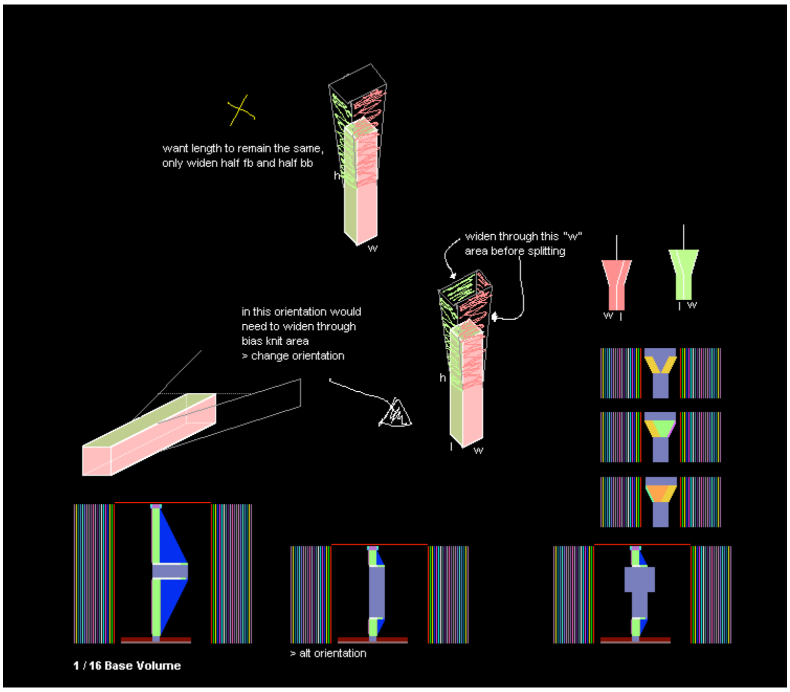


Figure 5.65
+ swell & taper, widening and additional carrier, 2018.

Figure 5.66
+ swell & taper, stitch lines, 2018.

Following the development of a widened cubic base, the introduction of an additional carrier[92] and the fabrication of two cubic branches required attention to be resolved. In this instance, packages for the construction of cuboids fabricated adjacent to each other were relatively straightforward, as the geometries were being constructed from within the component addressing the tubular knitting of the perpendicular planes. Knitting adjacent tubes from the stage of initialising a base, though feasible, would require significantly more programming.

In establishing the proportions of the widened base, the number of knitted loops necessary for accommodating two cuboid branches had been determined in such a way that the stitches held after widening the base were equal in number to those needed to integrate two additional 1/16 segments. However, mapping of the two segments onto the widened base required considerable experimentation (Figure 5.67 – 5.69).

It is in this aspect that the directional forces within the cloth and the reconciliation of stitch lines and orientation were most apparent. Some stitches from the two layers of front-bed and back-bed knitted fabric needed to be moved or manipulated in some way to create the inside edges of the two new segments. In this instance, the additional segment knitted on the right was rotated to reduce the twisting of yarn at the centre of the form. Though effective in reducing the twist, this is not an ideal solution and would not translate well into larger-scale outputs. Time constraints left this unresolved and requiring further research and development.

Populating + swell and taper

Additional geometries attempted in the category + swell & taper relate to spatial operatives *Taper* and *Pinch*. In these geometries and their derivatives (Figure 5.70), the shaping of the form is reliant on inside and outside widening and narrowing techniques.

As for the fabrication of bias-knit planes in the earlier section + ledge, the widening and narrowing techniques, and the format of their packages, were not intuitive actions. As such, iterative programming and fabrication cycles followed in the endeavour to balance the desired proportions of + swell & taper components, as well as the most effective positioning of the construction techniques to achieve directional stitches and shaping lines within the form. In the process of widening and narrowing the planes of a geometric form, the mapping to parallel needle beds was particularly complex when applied to all four planes of a cuboid. Aspects such as orientation and alternative openings were also accessed in these forms, as narrowing components often left standard openings inaccessible. Further, it was the inside narrowing and widening techniques that were used in returning to the unresolved *Inflate* derivative seen in Figure 5.62 and 5.70.

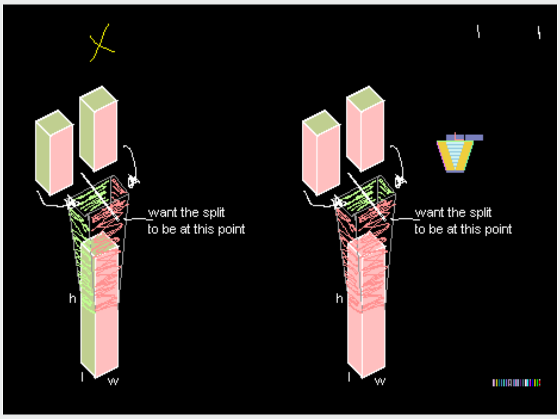


Figure 5.67

+ swell & taper, conceptual mapping of additional branches, 2018.

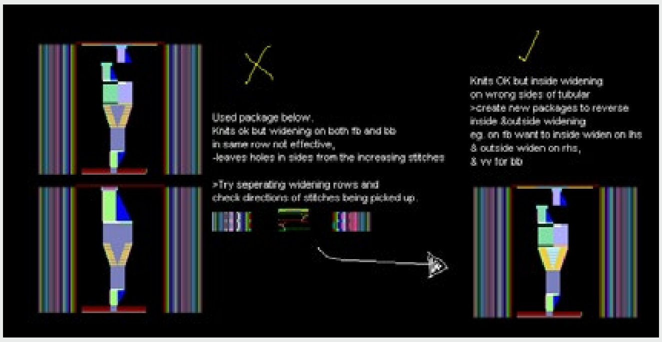


Figure 5.68

+ swell & taper, testing positioning and combination of widening packages for additional branches, 2018.

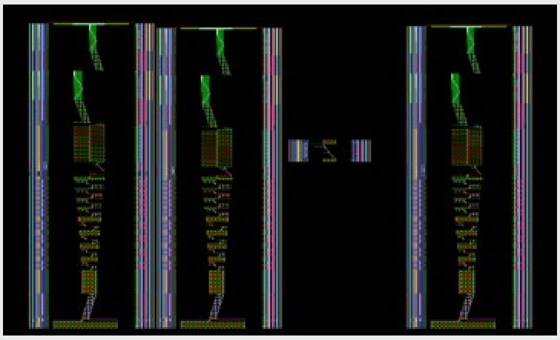


Figure 5.69

+ swell & taper, testing the transition from two volumes within the developed program, 2018.

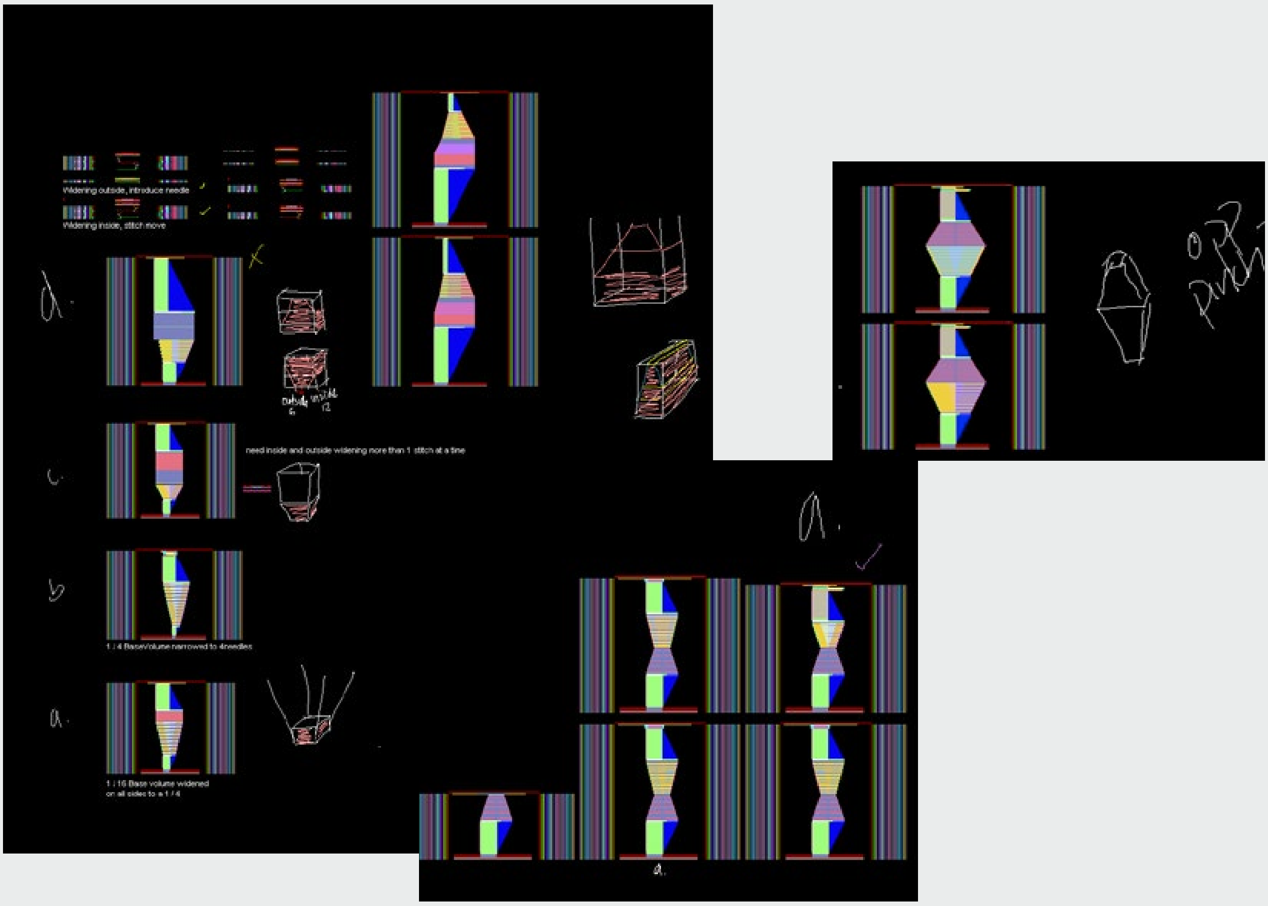


Figure 5.70

+ swell & taper, further derivatives, 2018.

Though a number of geometries were fabricated using these techniques, it is believed further experimentation is required to perfect a resolution for construction methods for geometries within this category. In the widening or narrowing of all planes of a geometric form it is thought that the parachute[93] construction concept could be of benefit. Unfortunately, time constraints and lack of experience with this technique meant it was not explored further within this study.

Extensions of + swell and taper

As for the action + wedge, discussed previously, the derivatives below are considered to sit within compositions. However, as they explicitly reference + swell & taper attributes within their geometric forms it is useful to describe and include them here.

In Figure 5.71, a split is created within the geometry by applying an inside widening construction technique, or more specifically, creating a wedge of additional stitches, within a tubular segment of knitting. Following this, the segment is partially closed before being extended again to create an additional tubular segment above the split that results from this partial closure. Once filled, the portion with the inside widening is seen to separate and bend where the wedge of additional stitches was integrated. In essence, the shape and positioning of the inside widening has the same directional impact on the geometry as for *Bend* in Figure 5.43, but the wedge or bend is added horizontally, within courses of knitting, rather than vertically by way of additional courses of knitting as for the geometric output of *Bend*.

Another set of derivatives using the +swell & taper attribute contains a notch within the form (Figure 5.72). In these geometries the cuboid base is partially closed before being extended vertically. The extended segment widens as a triangular wedge, leaving a notch effect within the geometry. The inside and outside widening are mapped in such a way that, used in combination, the notched planes mirror each other. Derivative B integrates a wedge into its cuboid base so that both the base and the extended tubular segment frame the resultant triangular notch.

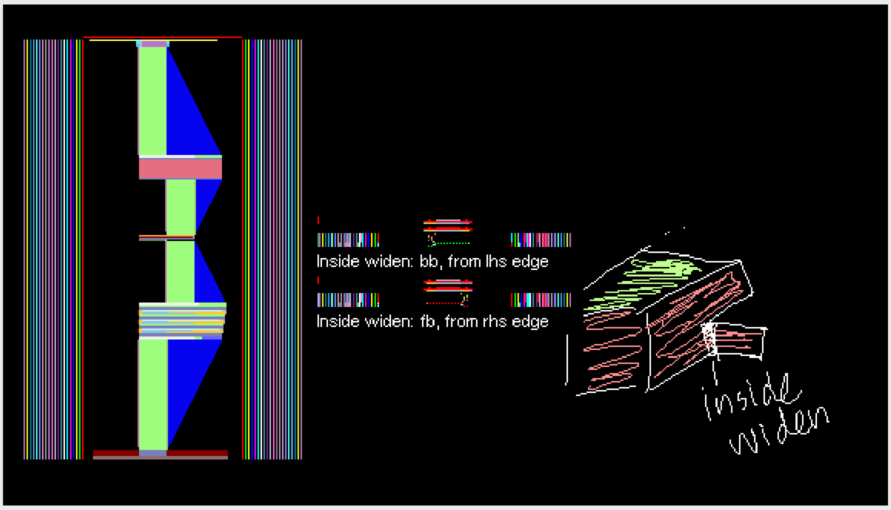


Figure 5.71
+ swell & taper, composition, 2018.

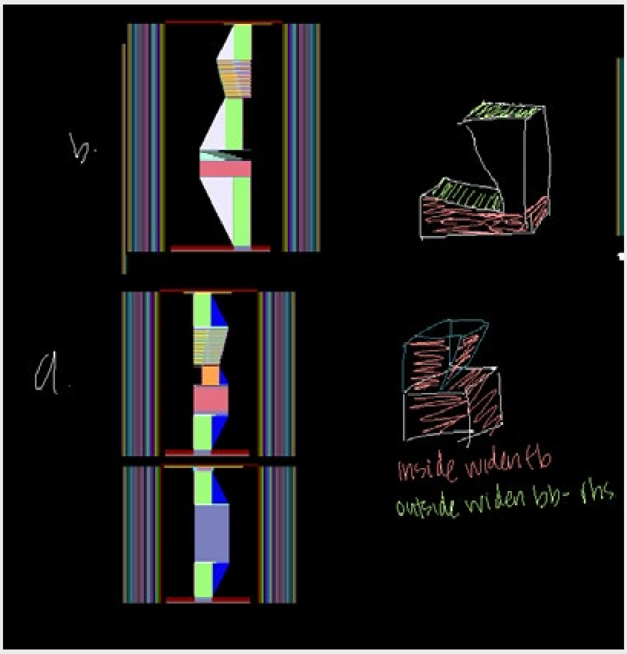


Figure 5.72
+ swell & taper, compositions, 2018.

+ hinge[94]

The category of + hinge (Figure 5.73) emerged from the linking of two forms through a component that acts as a fabricated join, first explored in Chapter Five, Part 1. It was noted then that an extensive range of variables can be incorporated within the hinge component. For example, hinges can be constructed in differing proportions or shapes, and different stitch types and yarns can be used. The subsequent impact these variables have on the directional forces within the resulting geometry, and the manoeuvrability of the forms being hinged, introduced further possibility to the sphere of 3-dimensional knitted form building.

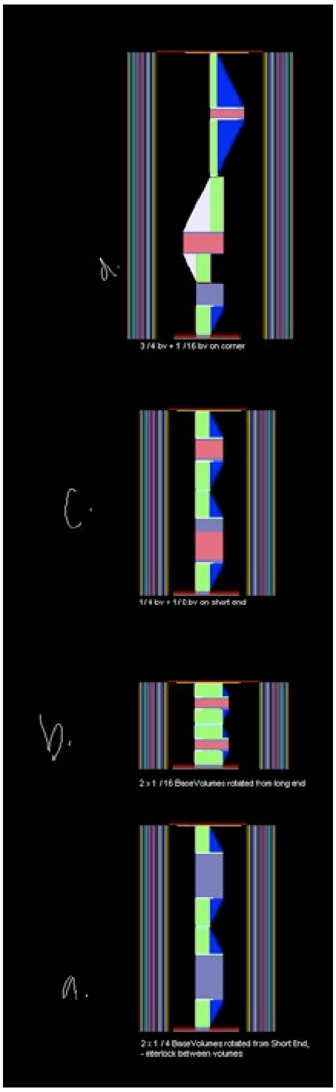


Figure 5.74
+ hinge, 2018.

In this research, the hinge component used an interlock construction technique to form a tight, narrow join between a range of cuboids (Figure 5.74). In this arrangement the hinge essentially allowed for geometries to pivot around a hinged edge. Given the materials and fill used in fabrication of these forms, the geometries retained this flexibility. Use of yarns which were stabilised post fabrication[95] or frames which could be fixed would allow for flexibility to pivot the form as required post fabrication before finishing with a stabilising technique, avoiding the need to fabricate exact rotation within a geometry.

In this range, the hinge was applied horizontally across the geometry, in line with the courses of knitting. Reorienting forms allowed for the hinge to be applied to width or length as required. Further research into the variables that can be incorporated into hinges, and their subsequent impact, would be beneficial for further geometric development and uses but was not possible within the timeframe of this study.

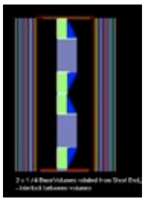
Operative

+ hinge

Attributes

- an independent component creating a join between two geometries

Compressed Program

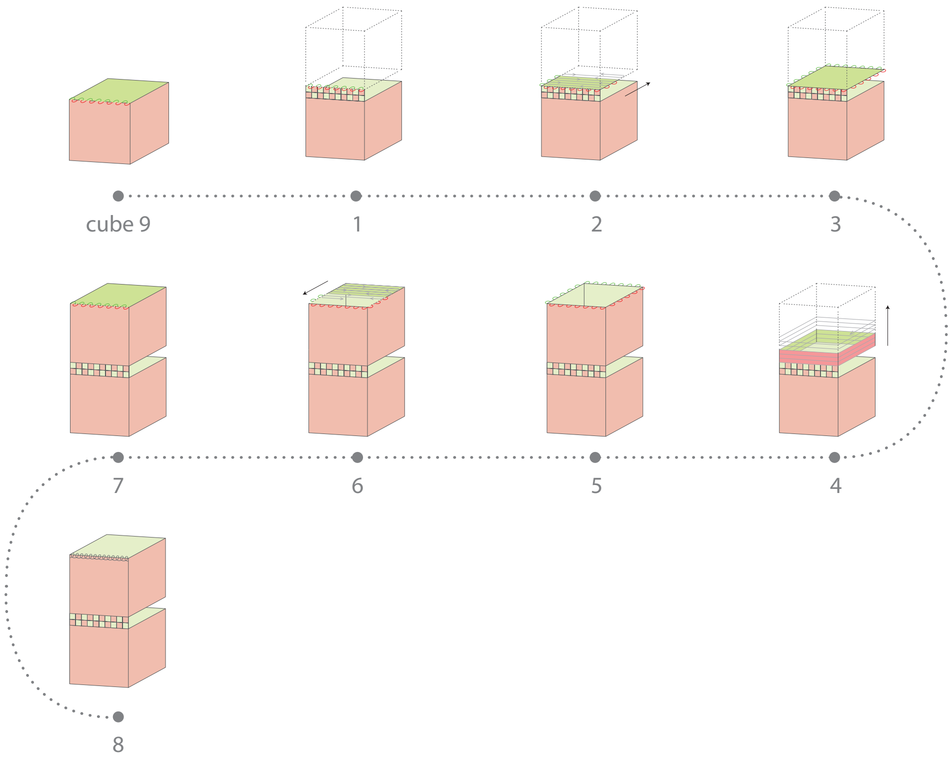


Construction Notes

- interlock

Fabricated Form

Process Mapping



- knit on front bed
- knit on back bed
- surface constructed on front bed
- surface constructed on back bed
- loop held on front bed
- loop held on back bed
- loop knitted on front bed
- loop knitted on back bed
- outline of intended form
- outline of constructed form
- direction of carriage
- direction of surface construction
- binding off

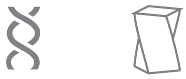
xviii

Figure 5.73
+ hinge, cubic form-building system, 2019.

Operative

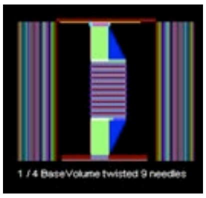
+ spiral

Attributes



- a rotational or twisting motion within a geometry

Compressed Program

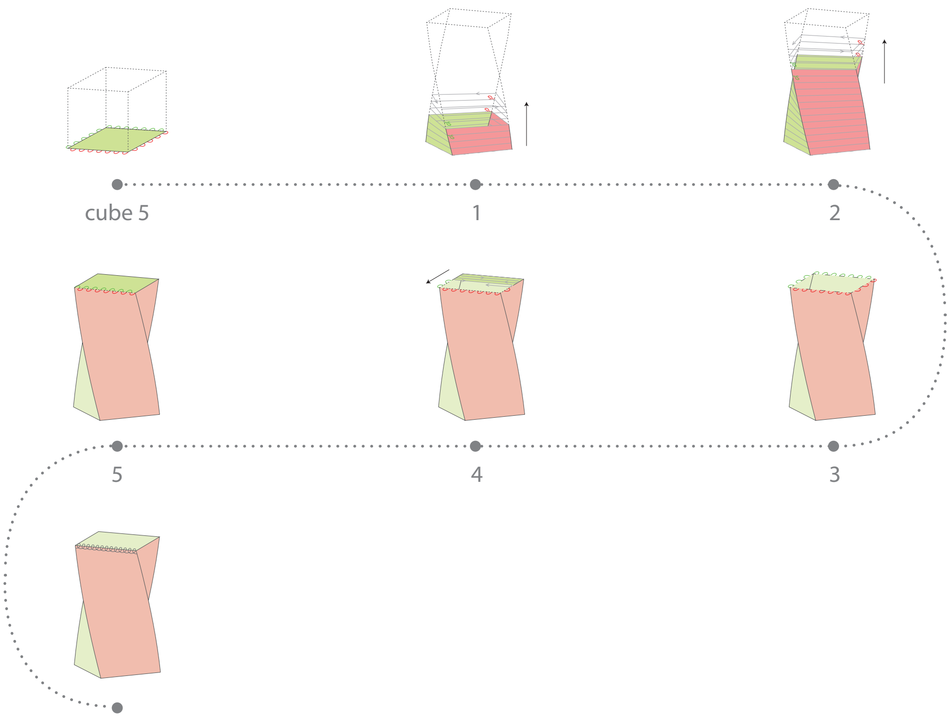


Construction Notes

- racking
- cross-bed stitch movement

Fabricated Form

Process Mapping



knit on front bed
knit on back bed
surface constructed on front bed
surface constructed on back bed
loop held on front bed
loop held on back bed
loop knitted on front bed
loop knitted on back bed
outline of intended form
outline of constructed form
direction of carriage
direction of surface construction
binding off

XX

Figure 5.75
+ spiral, cubic form-building system, 2019.

+ spiral

The +spiral operative (Figure 5.75) is reliant on the racking and rotation of stitches across front and back knitting beds; a concept first explored in the investigation of topological surfaces and, more specifically, the Mobius strip, in Part 1, Knit as Pliable Topological Surface.

In A (Figure 5.76) the geometry is initiated with a 1/4 Base Segment with a width of 18 needles. The planes are rotated 9 needles in total through this tubular section, so that a spiral effect is created around a central axis. More specifically, the closing plane at the top of the cuboid appears rotated by 45 degrees in comparison to the opening or base plane. The direction of the stitches on these bias-knit opening and closing planes further emphasises this spiral effect within the geometry.

In B (Figure 5.76), with a width of 9 needles, application of the same racking and rotation pattern as used in A creates a 90-degree rotation between opening and closing planes, and subsequently a more pronounced spiral.

These geometries were perhaps the most difficult to fill. As mentioned in Part 2, Materials and the Translation of Surface to Volume, geometries in which planes have a varying dimension or a dip within a plane are difficult to determine final filled measurements for.

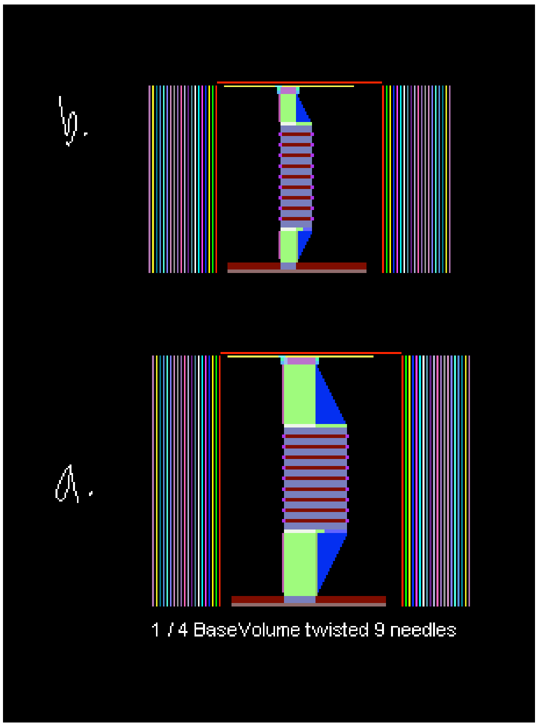


Figure 5.76
+ spiral, 2018.

Compositions

As the practice progressed, varying components and attributes of cuboid fabrications were revealed alongside the emergence of techniques and tools to support the required 2-dimensional to 3-dimensional translations and programming of geometric forms. Both aspects served to simplify the process of determining whether intended forms could be fabricated successfully.

Also emerging throughout the practice were considerations for how geometric forms or fabricated components could be combined into more complex forms as Compositions (Figure 5.77). Initially, the concept of combining geometric forms appeared relatively straightforward. If it was possible to fabricate forms as individual geometries, it seemed reasonable that there would be a method by which they could be combined to create a single amalgamated form.

As had occurred repeatedly throughout the practice, my initial reactions stemmed from reflecting on the geometric forms within a 3-dimensional space; as might be the case if physically fabricating the forms, such as with clay or 3-dimensional printing, or digitally fabricating outputs using CAD software. However, this thought process did not consider the fabrication of form, as the additive construction method of a geometric surface to be constructed on parallel needle beds.

Taking the geometric form's surface into consideration, it became apparent that the fabrication of initialised geometries or knit components was reliant on a predetermined orientation and sequence of construction. This often allowed for more effective or efficient programming, or in some cases allowed for the forms to be programmed at all. For an initialised geometry, or a single operative, orientation was not significant given the fabricated form could be freely reoriented for its end use.

However, in the design of integrated knit geometries there was just one possible orientation for each of the components relative to the base geometric form, or other components within its form. Crucially, to be successfully actioned, the orientation and sequence of components needed to allow for one component to end in a position or placement that allowed a further component to be integrated.

As geometries were extended and became more complex in their compositions, so too did the mental translation necessary to resolve actions required in programming the outcome. Further, as complexity and programming time increased, the opportunity to program and test the fabrication was reduced, requiring more heavy reliance on the capability to map out the construction and

Attributes		Construction Notes	Fabricated Form
- geometries composed of more than two operatives through an extend process	See Appendix A, Development Journey of 3-Dimensional Knit Geometries for detail of the extend process	- Merge: merging of two or more operatives to create a single programmed component - Integrate: sequential fabrication in which use of one operative follows the other	

Figure 5.77
Compositions, 2019.

determine feasibility of a successful outcome pre-fabrication. Though deeply embedded within the programming of geometric forms at this stage, and with new knowledge gained from the research, the fabrication of geometric forms past two or three iterations was difficult to translate mentally or diagrammatically.

As a consequence, a number of combination and aggregation concepts were started but not completed, due either to lack of feasibility, or the time and complexity of programming required. However, my knowledge base in this area grew with each form that was fabricated, as intuitive behavioural knowledge allowed a sense of what was possible, and it became easier to conceptualise feasible solutions.

The range of forms fabricated as compositions are shown in Appendix B and are annotated with the operatives used in their constructions.

Summary

In this phase of the research a range of cubic form-building operatives and their derivatives were investigated; a process in which a number of significant conceptual and technical insights surfaced. Conceptually, the most significant insight emerging from this phase of practice was the reinforcement of knitted-textile fabrication being bound by the underlying principles of its additive construction technique, and, therefore, the physical parameters of the technology. As fabrication within the textile domain concerns the production of surfaces or skins, rather than solid objects, the knitted geometric forms produced in this research form the boundaries of 3-dimensional volumes.

Further to this is the intrinsic nature of knitted cloth, in that it emerges from the continuous looping of a length of yarn and, in the case of WholeGarment technology, on parallel needle beds just millimetres apart. In this context, the unpacking of geometric forms for 3-dimensional knit fabrication is an incremental process: the continuous surface that encloses each volume is unfolded and dissected into knittable segments before being reconfigured in parallel planes and encoded in a 2-dimensional programming grid. From this process and its numerous complexities and translations, constructs of language, mapping and form have emerged.

In Chapter Six these constructs are further organised, reviewed and refined for dissemination. With the intention of supporting further exploration of 3-dimensional knitted geometries, the resulting methodology, tools and techniques are composed into the cubic form-building system presented in Part 2, Emergence of a Cubic Form-building System for WholeGarment Knit Fabrication, and Dimensions Unfolding: Manual of 3-dimensional Cubic Form-building in Appendix A.

84 The alternative option to fabricate this form using the widening techniques of + swell & taper was discovered later in the research.

85 The slide component in a package initiates a movement left or right to the length of the slide. In the compressed knit programs, the blue area represents a slide function. This allows for the bias-knit planes to be represented as a rectangular component in the compressed drawing, which is then expanded to knit on a diagonal, per the slide proportions within the developed program.

86 See Part 1, Extending Computational Literacy: A New Perspective of the Knitted Cube and Part 2, Base Volume and its Segments.

87 See Part 2, Openings and Closures.

88 This capability emerged from Part 1, Computational Literacy.

89 This is not a free, independent movement; yarn is moved by being carried left and right along the needle beds, forming knitted loops as it goes.

90 The fabrication of this form is presented in Cubic Geometry: In Structure Program & Form, in Appendix A.

91 Knit stability, fabrication time, quality and shaping lines are all impacted by the differing widening and narrowing techniques.

92 An additional carrier introduced in the last course of widening allows for the base segment to be split as two branches are integrated above.

93 Parachute shaping is a narrowing technique which allows for even distribution of stitches across the width of a surface.

94 Note this was called *multiples* at the exhibition; this change is discussed in Chapter Six.

95 For example, the use of thermal reactive yarns, which melt or harden to keep their form, could be used in the hinge to provide a specific pivot post fabrication.

96 In particular, Chapter Three, Language of 3-Dimensional Knitted Form and Chapter Five, Parts 2 and 3.

97 See Chapter Three, WholeGarment Design and Production for further detail of this context.

98 By way of example, + swell & taper uses widening and narrowing techniques that can be interpreted in a few ways. The use of the icon is more suggestive of the resulting geometry.

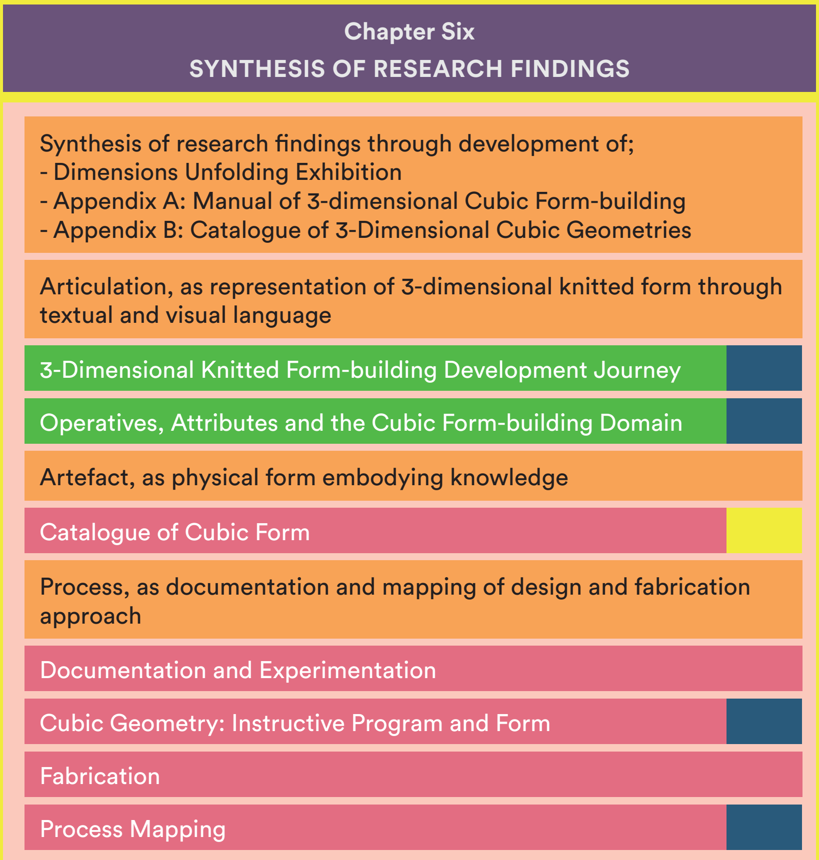


Figure 6.1
Practice framework, Chapter Six.

Chapter Six

Synthesis of Research Findings

In this chapter key research findings from the investigation of cubic geometries are synthesised through iterations of review and reflection to form components for presentation and dissemination (Figure 6.1). Initially, an exhibition of the research was held on 30 December 2018 at ST PAUL St Gallery, located at AUT. Alongside its intended role of presenting the research, the exhibition was also found to be a critical tool for advancing the research, revealing itself as a mechanism for consolidation and analysis. As a result, the components developed for exhibition emerged as significant articulations for 3-dimensional knitted form-building and were subsequently further developed in a form-building manual.

In line with the research intention of re-orienting 3-dimensional knit into a broader domain, the components range from conceptual and broadly understood to more technical fabrication-specific mappings. In combination, this format is intended to support access to, and exploration of, WholeGarment technology's 3-dimensional fabrication capability across a range of disciplines and skill levels. Some of the component development sits within the cubic form-building system and, as such, while referenced below, has been outlined in more detail in Chapter Five, Part 2, Emergence of a Cubic Form-building System.

The exhibition and manual were organised around three key themes, summarised in Figure 6.2. The following discussion details each theme and its components, considering both their emergence and intention. While the aspects addressed in this chapter represent key findings from the research, the dissemination through exhibition and manual did not cover the full range of research findings. A discussion about the conceptual findings and contributions of the broader research inquiry can be found in Chapter Seven.

Key Themes in Research Findings

Articulation, as representation of 3-dimensional knitted form through textual and visual language

Articulation concerns the expression of research findings in a range of representations for communicating varied aspects of 3-dimensional knitted form-building. As such, this theme considers textual and symbolic language for describing the operatives of 3-dimensional cubic forms, and graphic representations of form-building method to support ongoing investigation of WholeGarment's 3-dimensional fabrication capability.

Artefact, as physical form embodying knowledge

The knitted geometric forms constructed through the systematic investigation of 3-dimensional cuboid fabrication in Chapter Five, Part 3 are considered to embody the research findings, providing tangible, material evidence of the 3-dimensional cuboid form-building possibilities in the knit fabrication domain. In this format, the knitted forms provide a broader access to the advanced capability of WholeGarment technology, inviting further engagement and enabling communication across domain boundaries.

Process, as documentation and mapping of design and fabrication approach

As practice-led research, the processes, methods and insights of the practice are significant as a means for understanding practice as a source of new knowledge. Further, it is from the documentation of the making practice, and reflection on design and fabrication processes throughout, that the tools and mappings to support cubic form-building emerge. As such, this theme provides access to, and details the development of, the various tools, techniques and media that emerged to support the design and fabrication of 3-dimensional knitted geometries.

Figure 6.2
Key themes in research findings.

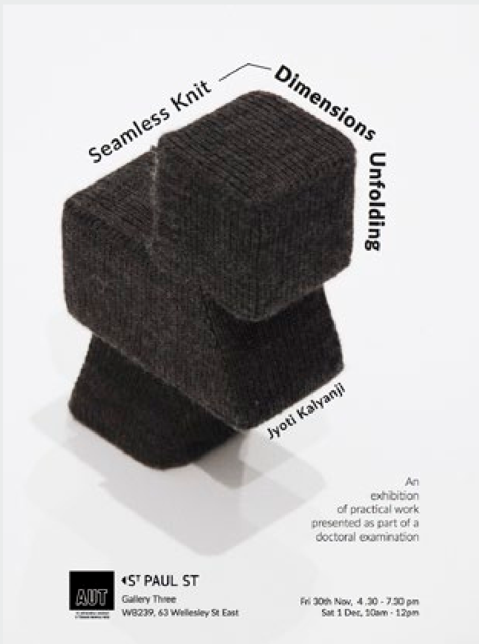


Figure 6.3
Exhibition flyer, 2018.

Exhibition

In line with its positioning as practice-led research in the design domain, the exhibition (Figure 6.3) formed part of the examination process. Essentially, this allowed examiners to view the practice and physical artefacts of the research before engaging with this, the written component of the thesis. Together the exhibition and thesis form the complete doctoral submission. In addition, the exhibition was opened to a broader audience and other design practitioners, in line with the research intention of reorienting WholeGarment technology for application within a broader design field, and for a broader audience. In this aspect, the exhibition played a role as an initial dissemination of the research findings.

Given these intentions, each component in the exhibition (Figure 6.4) was considered in terms of its ability to demonstrate design practice and/or research findings, as well as to support understanding and interpretation in the context of the exhibition being viewed by both knit practitioners and a non-specialist audience. Silve (2006, p. 10) notes, “In the stand-alone exhibition, the researcher is absent; in their choice to explain their research, they must carefully choose appropriate media to convey the message.” Rust and Robertson (2003, para. 24) further explain that supporting an audience’s understanding and reflection of the learning must be done, “in ways which are accessible to the whole audience for the exhibit, which will usually include people who have limited knowledge of the specialised issues addressed.”

The second role of the exhibition was revealed in the process of its organisation: the development and organisation of the exhibition as a research method in itself. In comparison to previous parts of the practice that were characterised by focused investigation of knitted geometric forms, the rapid iterations of review and analysis in this exhibition phase unfolded along multiple paths as findings emerged, and the varying components were built in parallel. In other forms or artistic inquiry, the exhibition is often used to engage an audience or elicit a response, which in turn forms part of the data creation within the research process (Savin-Baden & Wimpenny, 2014). In this research, rather than the external feedback from viewer interaction in the exhibition setting, it was the self-directed process of compiling exhibition components and the internal reflection and critical analysis throughout that revealed significant insights and connections in the research.

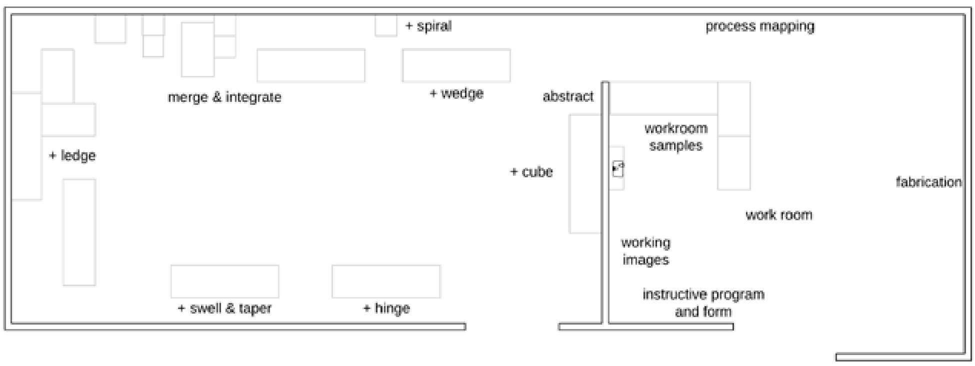


Figure 6.4
Exhibition floor plan, with the main gallery (left) and work room (right), 2018.

Manual of 3-Dimensional Cubic Form-building

A key insight from the exhibition was the need for an accessible format for the research findings. While the exhibition space allowed for physical artefacts and documentation to be shared in an interactive setting, the motivation for the research, to increase access and utilisation of WholeGarment technology within a broader design setting, required a more easily disseminated and interpretable format. As Nimkulrat (2007, para. 16) notes, “The artistic process is a series of interactions among different actors, such as materials, practitioner, and artifact. To transform an interactive process into evidence, it needs to be represented in textual and visual forms.”

Further, on reflection it was noted that while the examiners were provided with a synopsis before the viewing, and an abstract of the research was displayed within the gallery, the inclusion of text-based explanations for each of the components would have supported contextual understanding of the work and allowed for the components to be more easily interpreted by a broader audience. As cited in Silve (2006, p. 8), Cochrane (2004) notes, “objects only speak for themselves to people who know the language they are speaking.” Within such a specialist and distinct area, there are few who would know the ‘language’ of WholeGarment knit fabrication. Silve (2006, p. 8) goes on to explain, “without text, the object is unlikely to express its research component unless something novel about its construction or content suggests new knowledge.”

Further, while the knitted artefacts offered novel expression, in the intended research objective of reorienting WholeGarment knit technology into a broader design domain, the exhibition components presented in isolation did not indicate the full potential of this fabrication space, nor did they provide enough information to enable fuller engagement. In addition, the exhibition was limited to a specific timeframe and audience. It was recognised that a format enabling wider dissemination of the findings of the research was required.

In response, the Manual of 3-dimensional Cubic Form-building (Appendix A) was developed as a stand-alone resource that would allow practitioners from a range of backgrounds and levels of knowledge to engage with the 3-dimensional form-building capability of WholeGarment technology. The resources in the manual derive primarily from the components of the exhibition, which in turn, are representations of key research findings. As such, manual elements range from high-level broadly interpretable design concepts to more fabrication-specific construction mappings. Some of the more technical elements, such as the process mappings for cubic geometries, are included to provide insight into fabrication process and support the translation of design concepts into knit programs. However, they are they are not intended as technical templates and as such do not include specific programming code or instructions. Further accompanying the manual is a photographic Catalogue of 3-dimensional Cubic Geometric Forms (Appendix B).

Articulation, as representation of 3-dimensional knitted form through textual and visual language

The lack of language or visual representation for 3-dimensional knitted form and 3-dimensional form-building, and the difficulty and ambiguity that results from this absence, have been discussed at some length earlier in this thesis.[96] Further, in re-orienting 3-dimensional knit fabrication outside of the knitwear domain, the need to develop a broadly understood language or framework for representation and communication of form has also been noted. These concerns also surfaced in the design practice of this research, and it is in attempting to address these limitations that textual and visual representations have emerged.

More specifically, while articulations derived directly from the making practice, it was not until the knitted artefacts were viewed as a collection that the composition of the graphic, textual and symbolic representations of the knitted form-building system were established. As such, the articulations have been advanced through numerous iterations of review and refinement. However, it is expected that these will continue to evolve and expand as explorations of the form-building domain reveal more operatives and geometric forms.

The representations outlined here include a form-building development journey, operative notations and cubic domain representations. All are intended to be easily interpreted and, while positioned within a distinct fabrication environment, avoid the use of domain-specific references.

3-Dimensional Knitted Form-building Development Journey

The concept and development of a high-level form-building methodology emerged from review and reflection of the form-building process presented in the exhibition, where both operatives (Figure 6.7) and process mapping diagrams (Figure 6.21) were applied specifically to cubic geometries. Recognising that the form-building process that emerged from the practice was situated at a more abstract level, and that the cubic domain was not intended to be definitive of capability or possibility, consideration was given to the process being applied across a range of geometries. As such, while this component of the research was the last to be developed, it provides a conceptual overview of WholeGarment design and fabrication for the broader area of 3-dimensional knitted form-building.

The development journey presented here was revised numerous times as I sought to illustrate the process as a simple but informative overview accessible by a range of practitioners. Initially, actions and decisions were documented in a traditional flowchart to externalise the thought process behind cubic form-building. Testing and evaluation against the construction of various geometric forms allowed for improved clarity in the method so that it was better able to be abstracted and shifted from the cubic domain to the broader area of 3-dimensional knitted form.

At this stage, the objective of the development journey was revisited. The graphic was intended to be interpretable by a range of practitioners, whether from design or technical backgrounds. Further, it was observed that the original charting related specifically to the technically oriented programming process of WholeGarment knit production. As a result, the graphic was further developed into a higher-level form-building process showing the technology's positioning within a system of design and fabrication, and which could be applied across an expanding library of operatives and forms.

Moving the focus from knit programming decisions to a more conceptual model was also considered critical to supporting the variability needed to stimulate creativity and inventiveness in 3-dimensional form, as opposed to the automated processes that can result from traditional flowcharts. There is a risk that a form-building methodology, or development journey, simply provides another version of a highly abstracted interface, as is the case with the technology's garment silhouettes, and that the creative capability of the technology is once again being masked behind established methods of form building.[97] Maher (1990, p. 49) notes, "There is a need to identify models of design processes that facilitate design rather than prescribe a design process." In addressing these concerns and with the intention to avoid prescriptive or suggestive paths within the form-building journey, the iterative cycles of development in the journey encompass the potential for extended geometries. Further, the graphic avoids the use of domain-specific language or language suggesting function.

Two versions of the form-building journey were developed, both of which appear in the manual. The first (Figure 6.5) is a generic WholeGarment form-building development journey for application across a range of geometric forms. The second applies this methodology within the domain of cubic geometries, populating it with the operatives revealed to date (Figure 6.6).

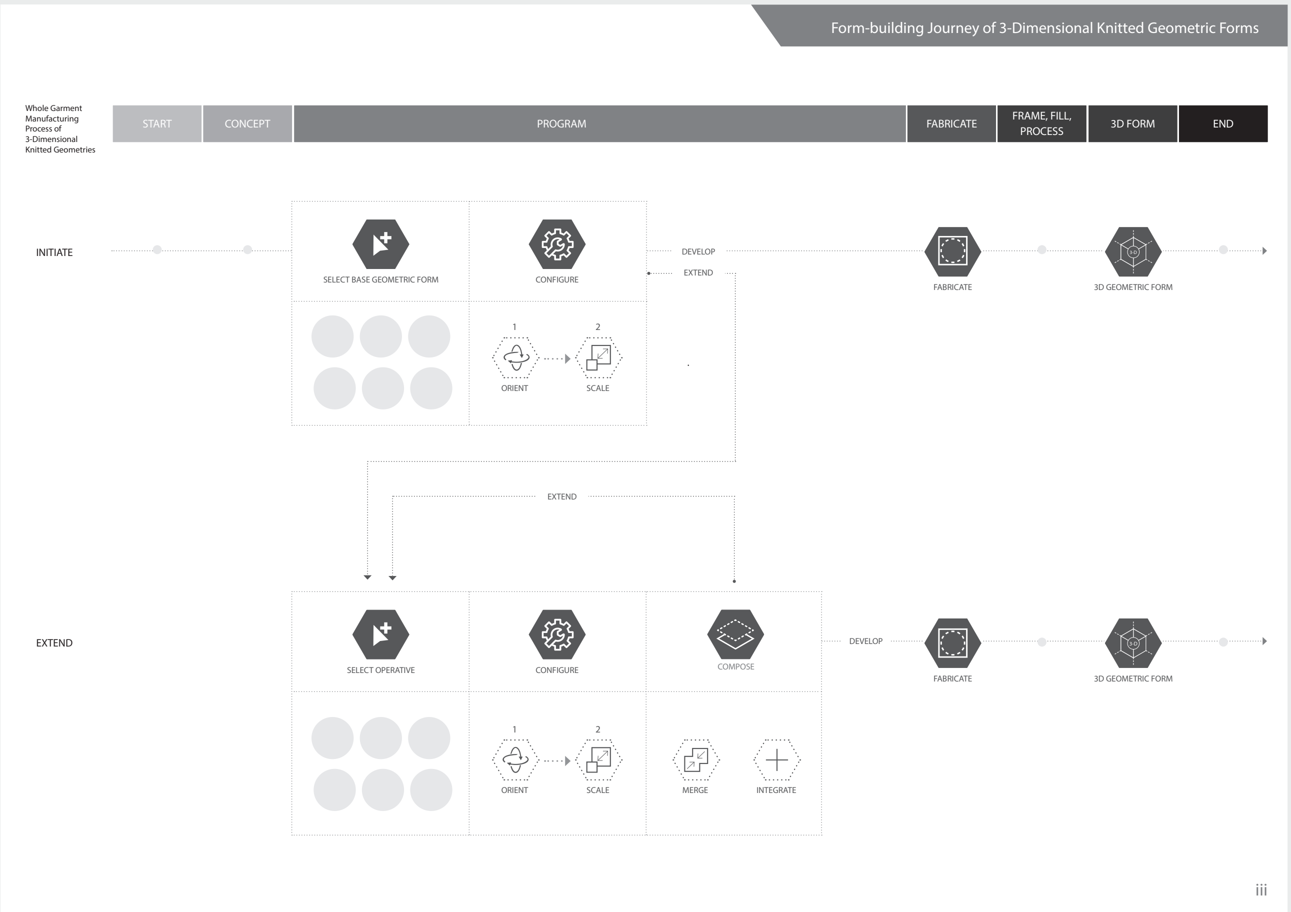


Figure 6.5
Development journey for knitted 3-dimensional geometric forms, Appendix A, 2019.

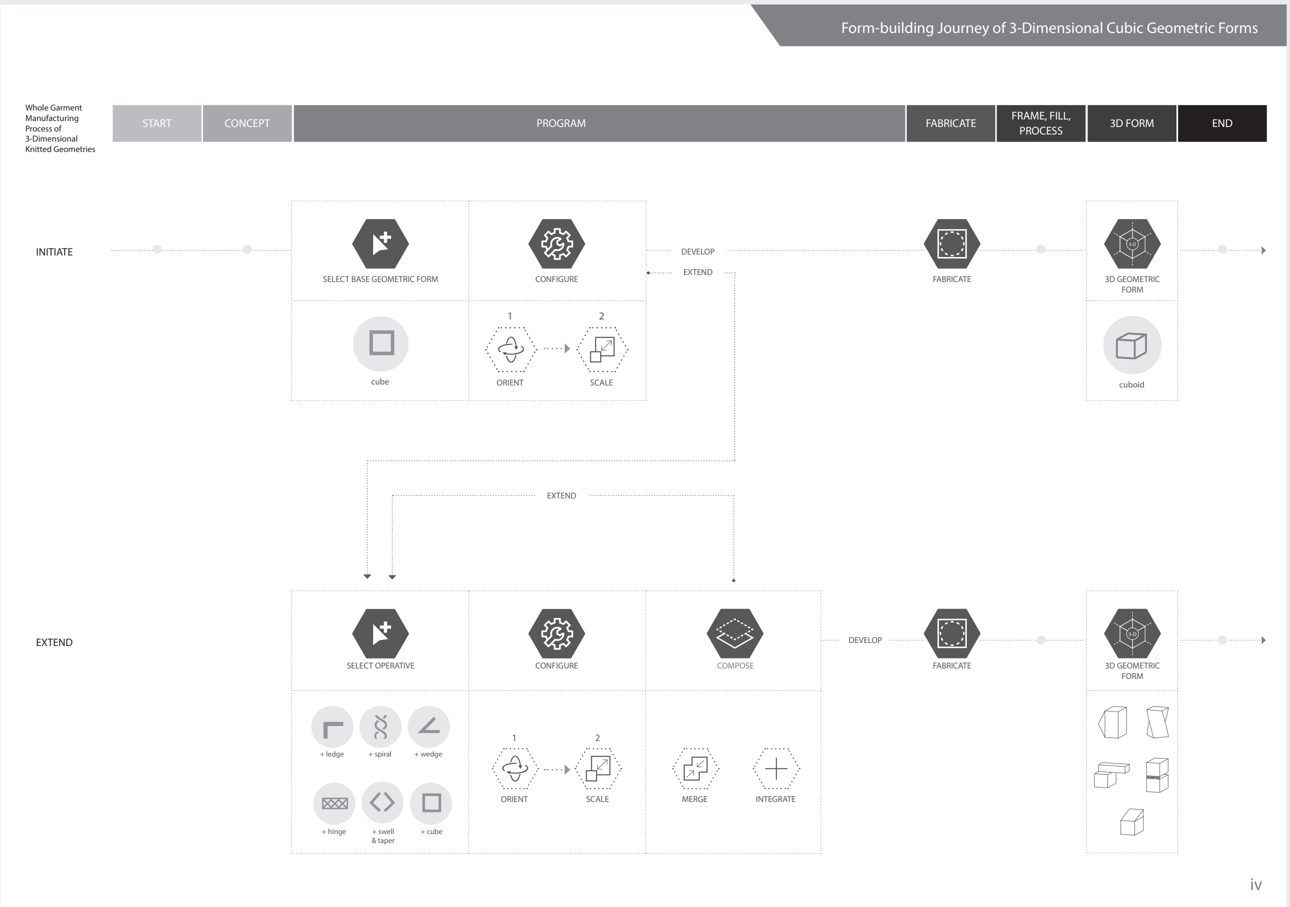


Figure 6.6
Development journey for knitted 3-dimensional cubic forms, Appendix A, 2019.

Operatives, Attributes and the Cubic Form-building Domain

The operatives presented in the form-building journey of the previous section represent the spatial actions, or shaping, embedded within a fabricated form to create a specific geometry. The need for operatives specific to the knit fabrication domain emerged through the development of cubic geometries as outlined in Chapter Five, Part 2, Investigation of Knitted Cubic Form-building. As operatives evolved, they were initially identified through the technical construction of their shaping. While adequate for self-directed practice, this did not allow for comprehension of the findings by external parties, nor did it provide a strong depiction of the resulting geometric forms. As a result, the operative names and notations were translated into more legible and suggestive articulations, the development of which is detailed in Chapter Five, Part 2, Operatives.[98]

As a means of charting these operatives and providing an overview of their positioning and potential within the cubic form-building domain, the diagram shown in Figure 6.7 was developed. The format of the diagram was intended to be suggestive of cubic form-building potential, in that the cube at the centre can be extended through the application of various operatives into a range of derivative geometries and that, in turn, each of these operatives or derivatives can be merged and/or integrated to produce further variations. In combination with the text and visual elements, the diagram aims to be interpretable by practitioners from varying backgrounds.

As for the form-building journey discussed previously, the importance of highlighting operatives, rather than a range of their fabricated geometric forms, is a deliberate attempt to offer a framework that minimises prescriptive design outcomes, and instead allows for innovative form-building. As such, the diagram is not intended to be definitive, and recognises that the domain has only begun to be populated with regard to proven operatives and fabrication. Nor does the research assume the operatives revealed to date are the only possibilities, or that these could not be expressed or arranged in other ways. Rather, it is expected that this domain will continue to expand and evolve as further operatives are revealed. From this stance, the operatives are seen to contribute to an expanding library of shaping components that can be accessed for 3-dimensional knitted form-building.

Following the exhibition, the graphic system was revised to reflect changes in operative names and visual representations. The naming of each operative category was intended to be suggestive of its geometric form, as both volume and surface, while also being suggestive of the additive knit construction technique that creates that geometry. Three key changes were made in the language within the cubic form-building system to reflect this intention.

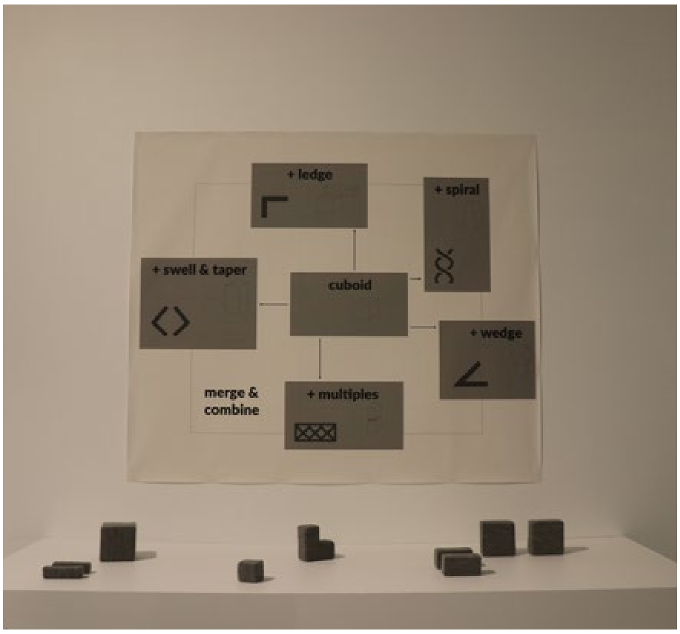
Multiples » Hinge

Initial naming of this operative was focused on the multiples that can be fabricated through applying this operative within a single form, essentially creating a repeat, or tessellation. As such, while the other operative names largely reference the constructive action being taken to fabricate a geometric form, 'multiples' corresponds more directly to the form resulting from the action.

Further, the operative grouping is concerned with extending a form through the application of a join, regardless of whether the forms being joined are similar or not. In this sense, the idea of multiples or repeats is confusing. Returning to the constructed action being taken, the naming has been revised to focus on the join. The word 'join' itself can be interpreted in many ways within the fabrication process, while the notion of a hinge specifically addresses the flexibility inherent in the knitted join of closed forms.[99]

Merge and Combine » **Merge and Integrate**

Reflection on the form-building system following the exhibition led to the high-level development journey discussed in the previous section. Through this process it became apparent that the concept of combining operatives was essentially an additional iteration of a merge or integration. That is, to extend cubic geometries, selected operative components could be merged or integrated[100] and that this process could be repeated as many times as required. In order to clarify this process and connect this diagram to the form-building journey above, the terms were revised from 'merge and combine' to 'merge and integrate.'



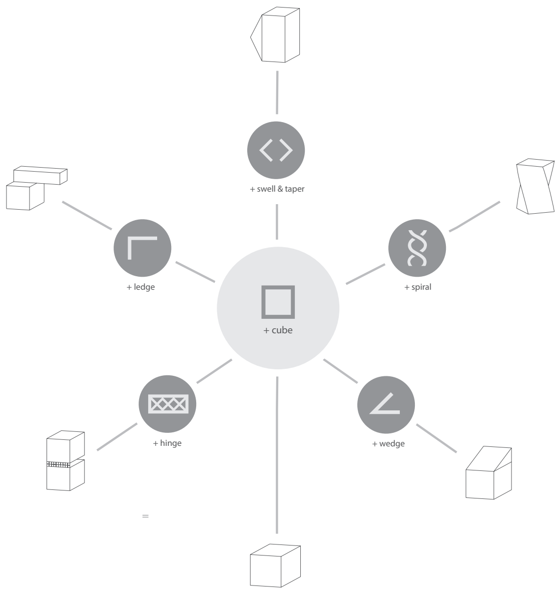


Figure 6.7
Cubic Form-building Domain, *Dimensions Unfolding* exhibition (left) and manual (right), 2018.

Cuboid » Cube

The term cuboid encompasses a range of cubic forms, whether sides are even, as for a square cube, or uneven, as for a rectangular cuboid. In essence, all forms are initiated from a square cube, which in this practice was the 1/1 Base Volume. It was from this form and its corresponding knit program that all cubic variations were derived, and as detailed in Chapter Five, Part 2, Base Volume and its Segments, a cuboid resulted from altering the scale and/or orientation of the base cube.

As such, the term cuboid was revised to cube. In addition, an icon and line geometry were added for the operative, acknowledging that this component sits among the library of operatives, and can be selected to be merged or integrated along with the other components.

Other changes made following the exhibition were centred around modifications to the format in order to improve its reading. As such, the graphic is intended to provide an indication of operatives that have been used to date, as well as being suggestive of the range of geometries that can be fabricated within the cubic form-building domain.

Artefact, as physical form embodying knowledge

As discussed, ongoing commentary around possibility in 3-dimensional knitted form has remained largely speculative, with limited demonstration of what is possible. As tangible artefacts, the fabricated forms resulting from the systematic investigation of cubic geometries documented in Part 3, are seen to embody the new knowledge of the design practice, bringing some definition to the domain of 3-dimensional cubic forms. Further, as proven capability, the collection serves to extend Gero's (1990) notion of the 'space of possible designs' within the knitted textiles domain, discussed previously in Chapter Three. More specifically, this collection represents a distinct area of fabrication, identified by its use of held stitches to knit planes in different directions in the construction of seamlessly knitted 3-dimensional geometries.

The knitted artefacts were displayed in the main gallery in their operative groupings[101] (Figure 6.8) and were all filled and closed, in line with the process described in Chapter Five, Part 2, Openings and Closures. In this format, the extensive range of form-building possibility within each operative was reinforced. Further, each group was labelled with the operative name, using both text and icon[102] as a naming convention (Figure 6.9). The inclusion of icons provided a more immediate visual representation for the shaping activated within the fabricated form while also allowing a more technical reading of the form's construction.

Figure 6.8
Dimensions Unfolding exhibition, main gallery, 2018.

Figure 6.9
Dimensions Unfolding exhibition, operative iconography application, 2018.

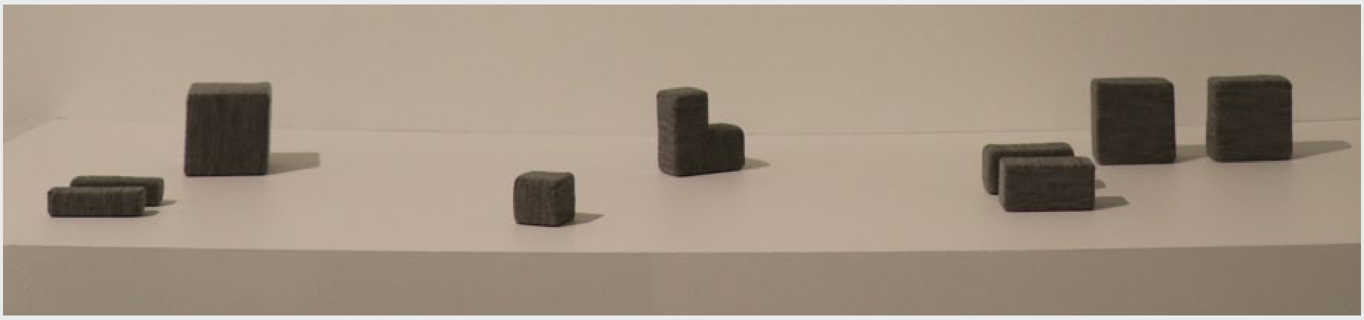


Figure 6.10
Dimensions Unfolding exhibition, Base volume and its segments, 2018.

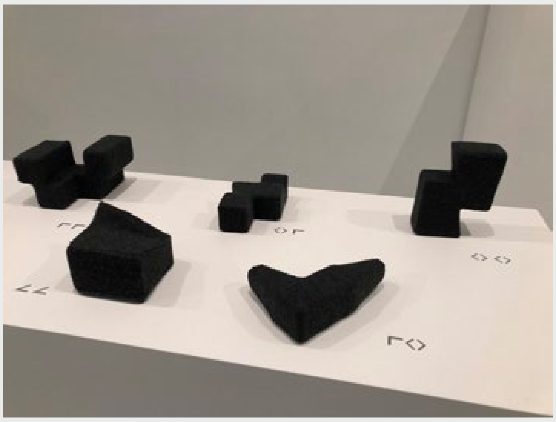


Figure 6.11
Dimensions Unfolding exhibition, Compositions, 2018.

The display in the main gallery also included the base volume and its segments, which were presented at the entrance of the gallery (Figure 6.10), differentiating them as foundations or base forms[103] from which the other operatives derived. A collection of merged and integrated geometries from Chapter Five, Part 3, Compositions was also exhibited (Figure 6.11). These geometries were identifiable by the darker grey yarn used in their construction and were labelled with the range of operative icons used in their construction, allowing viewers insight into their fabrication.

Catalogue of Cubic Form and Shared Understanding

Access to a large gallery space before the exhibition allowed for all the artefacts to be laid out and viewed as a collection for the first time. As detailed in Part 2, Emergence of a Cubic Form-building System this proved beneficial for iterative review and reflection and, subsequently, the categorising of the knitted geometric forms into operatives. Also significant in these reflections was ongoing consideration for this collection of artefacts as a digital catalogue of knitted cubic form such that the form-building potential of WholeGarment fabrication, and the knowledge embodied within these forms, could be more widely shared. In the development of non-garment product, in Chapter Five, Part 1, Interdisciplinary Projects, the absence of proven samples meant there was limited available reference with regard to explaining or suggesting design concepts. Combined with a lack of shared understanding among collaborators, this was seen to hinder innovative development and application.

As fabricated and filled forms, the geometries in this collection were easily understood. In this sense the knitted artefacts functioned as boundary objects. Such boundary objects are said to allow distinctive and specialist knowledge to be represented in a structure that allows for interpretive flexibility. In addition, the fabricated forms assumed the role of look and feel prototypes.[104] As relatively neutral objects, without particular visual or haptic aesthetic qualities and void of preconceived notions of product or function, the artefacts were suggestive, allowing the viewer to interact with and reimagine the geometry in a variety of aesthetic and functional formats.

Following the exhibition, with the intention of developing a means of shared understanding and demonstration of capability, the knitted artefacts were photographed and assembled into a catalogue according to operative groupings. While not enabling interaction with the physical forms, the images still invite engagement through easily deciphered forms.

The catalogue is formatted so that each artefact is annotated with both text and icon for the operative applied in its fabrication. For geometries in the Compositions category, distinguished by the use of more than one operative in their fabrication, all operatives are presented in the sequence in which they are applied (Figure 6.12).[105] As for the form-building methodology, the use of operatives in this way could be read by an experienced knit practitioner, as high-level programming instructions.

As a supplement to the *Dimensions Unfolding* manual, the photographic catalogue demonstrates possibility within the domain of 3-dimensional knitted cubic forms. However, it is not intended to define the population, or the boundaries of this domain; rather it is intended to be suggestive of the potential within WholeGarment's advanced fabrication capability.

Process, as documentation and mapping of design and fabrication approach

This area played two key roles in this research. First, as practice-led research, the processes, methods and insights of the practice were significant as a means for understanding practice as a source of new knowledge. For this reason, access to documentation and experimentation of the design practice was considered as central for the purposes of examination. Further, the inclusion of visual media to demonstrate programming and fabrication processes supported understanding of WholeGarment's distinctive manufacturing process and, more specifically, the complexities of knitted form-building.

Secondly, it is from documentation of the making practice, and reflection on design and fabrication processes throughout, that the tools and mappings to support cubic form-building derived. An early iteration of these elements was shown at the time of exhibition, with all aspects being developed further for the form-building manual.

This theme was addressed in two parts: the first being direct access to practice workings and experimentation, and the second outlining elements of the programming and fabrication stages for the development of 3-dimensional cuboid geometries, including instructive programs and process mappings.

Documentation and Experimentation

Documentation and sampling from throughout the practice was displayed on tables in the back room of the gallery, allowing access to, and transparency of, the design practice (Figure 6.13). For a textile designer, the tactility of the knitted cloth, tensions and directions of stitches, and flexibility in knitted geometric forms are all meaningful interplays in the process of form building. In my practice, interaction with the fabricated form was critical in progressing the translations required for 3-dimensional knitted form-building, particularly with regard to the mapping of planes and orientations of geometric components. Presenting these largely unfilled experimental samples allowed the audience to similarly examine and interact directly with knitted form as part of a form-building process (Figure 6.14).

Figure 6.12

Compositions, bent cubic form, Appendix B, 2019.

Figure 6.13
Dimensions Unfolding exhibition, work room, 2018.

Figure 6.14
Dimensions Unfolding exhibition, work in progress table, 2018.

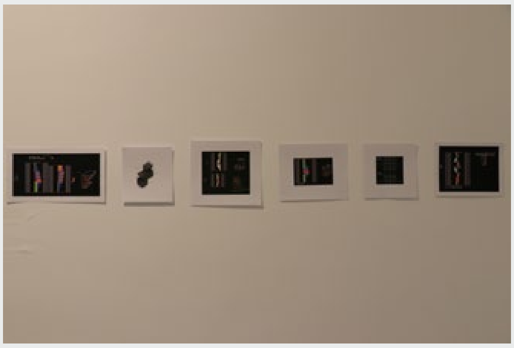


Figure 6.15
Dimensions Unfolding exhibition, sketches and reflections, 2018.

Figure 6.16
Dimensions Unfolding exhibition, instructive program and form, 2018.

The images on the wall (Figure 6.15) included annotated sketches and reflections recorded in both the Shima Seiki software and journals throughout the practice.[106] The lack of a mechanism for representing or visualising 3-dimensional form within the WholeGarment design system resulted in the conceptualisation of geometric forms and mapping of planes becoming reliant on my own illustrations and diagrams. Of significance, these hand-drawn sketches evolved into the digital sketches of the Process Mapping Diagram, detailed to follow.

Programming, Fabrication and Form

This component of the findings consisted of a range of media intended to demonstrate key stages of the programming and fabrication of 3-dimensional forms within the WholeGarment environment. In addition, this combination of elements allowed observation of a distinct and generally inaccessible knit manufacturing process to be viewed by a broader audience and, in turn, provided a context for the research inquiry. The following discussion details the process or development journey in the programming and fabrication of a large-scale cuboid form exhibited in this space.

Instructive Program and Form

In this element compressed and developed knit programs for a cubic geometry were displayed alongside the fabricated form, allowing insight into the translations between 2-dimensional programming grid and 3-dimensional form (Figure 6.16). For this purpose, the form was left unfilled and was mounted in such a way that it could be removed and examined in relation to the corresponding knit programs. The 'yarn in,' waste, and 'tail'[107] were intentionally left on the fabricated form so that its start and end points, or orientation, were easily determined. The form was constructed in different-coloured yarns, with each yarn colour representing a different construction technique or package within the compressed drawing.[108] As a result, when presented in conjunction with both its compressed drawing and developed program, the artefact provided a tactile reference, allowing the planes and intersections of the 3-dimensional geometry to be more easily mapped to the 2-dimensional knit programs.

The concept for this artefact evolved from personal reflection. As discussed previously in Chapter Five, Part 3, + ledge, interaction with the fabricated form was often necessary to assess accurate mapping of planes, edges, corners, stitch directions or other such features to the 2-dimensional knit programming grid. However, as geometries became more complex, or with limited understanding of the translations and knitting techniques, it could be difficult to map these elements of the knit program onto 3-dimensional form, and vice versa, even after fabrication.

In addressing this complexity, this large-scale colour-coded artefact was developed. The use of colour simplified the mapping by allowing the transitions between construction techniques and the subsequent changes in stitch directions to be easily distinguished. In Belcastro's (2009) paper, referenced in Chapter Five, Part 1, Knit as Pliable Topological Surface, the author notes the use of knitted topological objects as learning tools to support understanding of complex non-orientable geometries. Similarly, as a reference tool to support explanation and understanding of the numerous translations required in programming a 3-dimensional geometry, this set of artefacts offered a visual connection between knit program and fabricated form.

The geometric form chosen for this purpose contained bias knit planes on both back and front beds; a significant finding in the research, which vastly extended the breadth in the range of cuboid forms that were fabricated. In addition, while the geometry was somewhat complex in its programming it remained relatively direct in its translation to the knit form, in that each plane of the geometry could be visually isolated and mapped to the form. From a technical perspective, the construction of this geometry was initiated with a cuboid base, before being partially closed from all four sides. The opening that remained accommodated a smaller cube, which was integrated on top of the base. A large-scale filled version of this form was also displayed at the exhibition, though in a single colour (Figure 6.17).

As an artefact that could be mapped to its 2-dimensional knit programs, the model was useful both in composing knit programs and in reverse, when attempting to map a constructed form back to its program. While there was still a degree of trial and error in 3-dimensional fabrication, and as geometries were assigned more specific functions, there remained a need to resolve technical issues or shaping via interaction with the fabricated form. Even when the nature of a construction issue might have been known, it was not always obvious which component of the program corresponded to the fabricated plane or stitch(es) in question. The colour differentiation within this sample assisted with mapping in both directions and could be used as a guide in mapping of other geometric forms.

The artefact also supported consideration of the possibility or feasibility of extending cubic geometries. Though a range of fabricated artefacts resulted from this research, the corresponding programming and construction was not always obvious. Consequently, it could be difficult to assess where fabrication started and ended, and where opportunities to extend planes might have existed within the form. In this regard, the fabricated form and its programs functioned as a physical prototype from which additional planes and their positioning could be determined; essentially providing a physical indication of potential points of departure for extending a fabrication.

Figure 6.17
Dimensions Unfolding exhibition, filled cubic artefact, 2018.

Following the exhibition, this set of programs and the unfilled fabricated form were developed into an annotated diagrammatical reference (Figure 6.18 and Appendix A). Though the artefact is not able to be physically examined in this graphic format, the use of coloured yarns is still effective for distinguishing between program components and allowing for each change in knit technique to be detailed.

There are two key objectives in the annotations. The first concerns the translation from 2-dimensional program to 3-dimensional geometry in that each plane of the fabricated artefact, represented by a change in colour, is directly linked to its corresponding section within its knit program. Though the fabricated artefact cannot be examined physically, this graphic linking of planes to program allows for some of the learning to be retained in an accessible format.

The second objective is to provide an indication of the construction technique through which each plane emerges. In aiming to keep the manual as a non-technical accessible resource, the annotation is kept brief, providing enough information that a practitioner could seek further technical details if required, while allowing for the resource to be suggestive in the exploration or realisation of alternative geometries.

Fabrication

The fabrication process was represented in the exhibition by means of a video recording showing the programming and production of the coloured cubic geometry discussed in the previous section. As such, the recording connects the knit programs with the construction of the fabricated geometry, showing the developmental journey of a 3-dimensional knitted form. The process shown in the recording includes programming on the WholeGarment design system, transfer of data to the WholeGarment machine, construction of the knitted form and lastly, the fabricated form being released from the machine. Figure

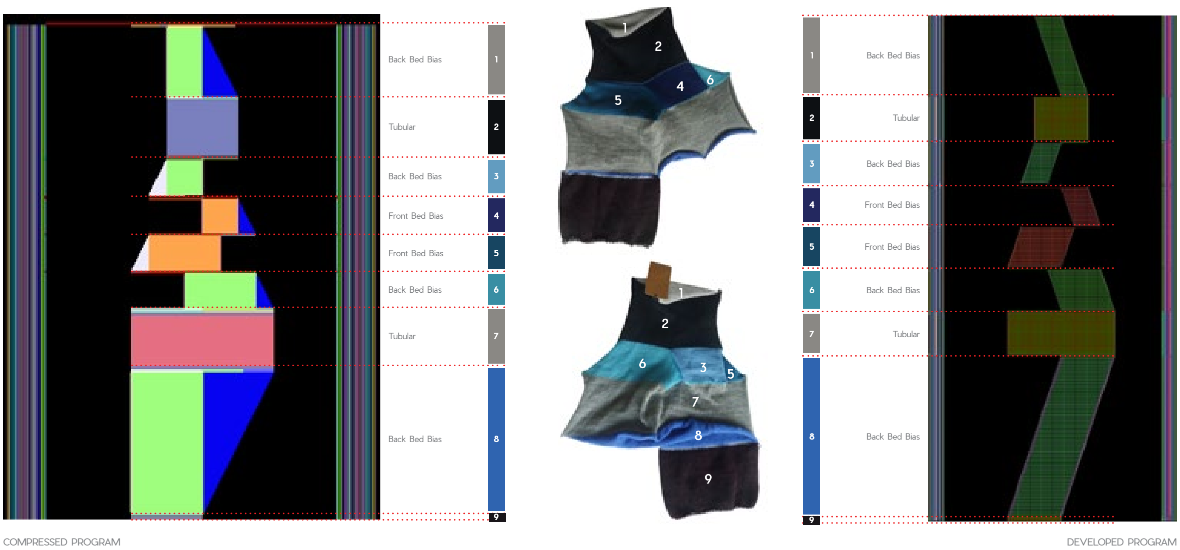


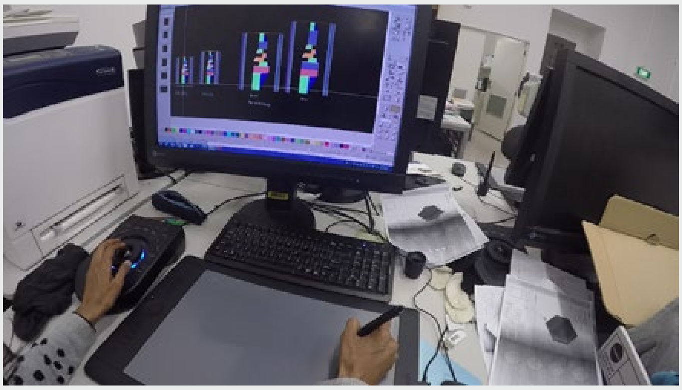
Figure 6.18
Cubic Geometric Form, Instructive Program and Form, Appendix A, 2019.

6.19 shows the recording as projected in the exhibition setting while Figure 6.20 shows some stills from the recording.

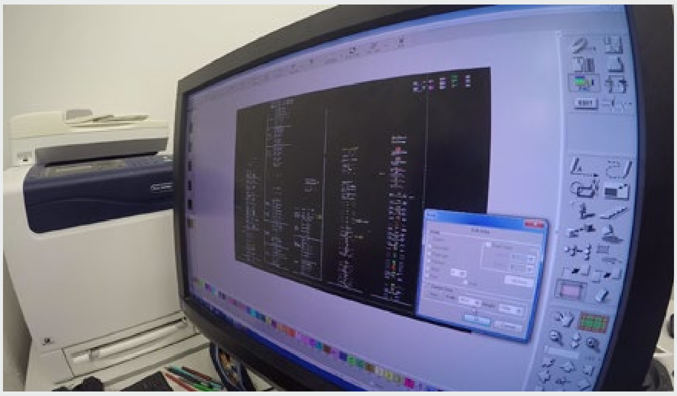
The representation of the fabrication process, and the use of moving image for this purpose, rather than static images or textual documentation, has several benefits. One of the objectives of this research is the reorientation of the WholeGarment knit system as an additive fabrication technology for a broader design audience. Both in support of such a reorientation, and as a context for the existing research for a non-knit audience, the video recording was effective in providing a view of the fabrication system as a whole, rather than just the design or programming. Silve (2006) notes the use of video in an exhibition setting to, “enable the viewer to reach a deeper understanding which, in the case of video, often entails an attempt to bring them closer to the experience of the process at the heart of the research.” In this regard, the recording is seen to allow access to the WholeGarment fabrication process while the physical size and sounds of the machinery serve to highlight its positioning within an industrial manufacturing environment.

An additional motive for including this medium was that it reinforces the distinct construction methods of WholeGarment knitting. The ability to view fabrication in motion provides a strong illustration of the emergence of 3-dimensional forms from a construction space spanning parallel knit beds. In turn, this verifies the nature of the fabricated textile as skin or surface, emerging from the machine as a flat, manipulatable and unrecognisable form, and further highlights the complexity in linking the parallel planes of the knitting machine to 3-dimensional geometry and 2-dimensional programming grid.

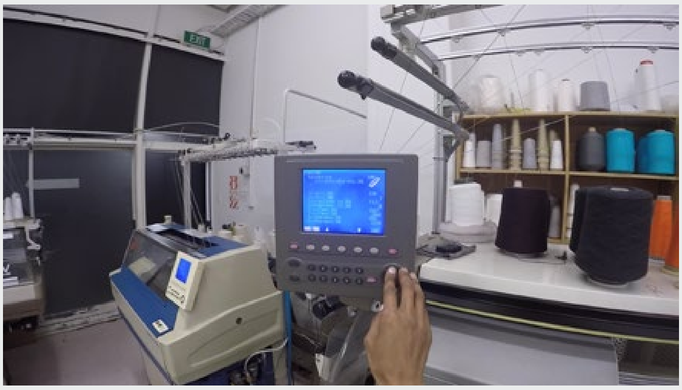
Figure 6.19
Dimensions Unfolding exhibition, video installation, 2018.



Programming

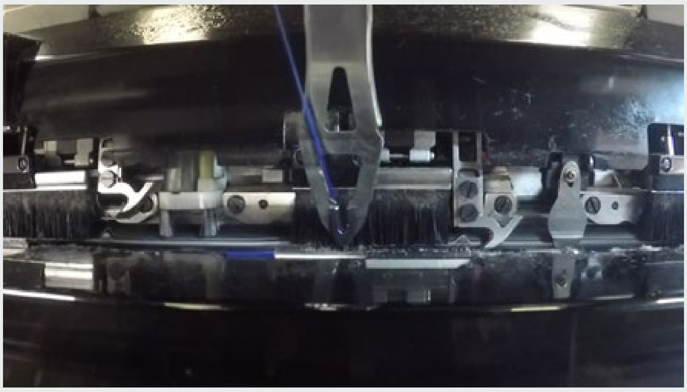


Packages



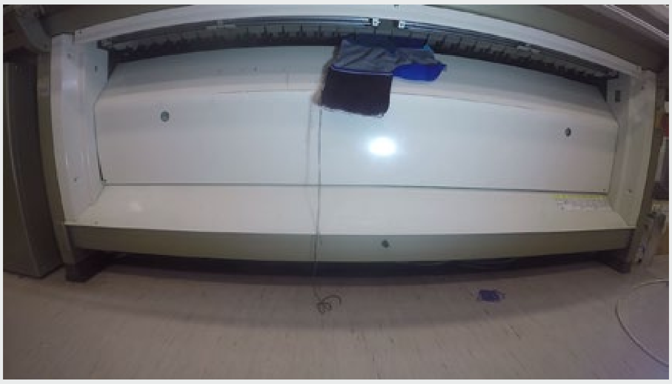
Loading program

Yarn feed through laterals

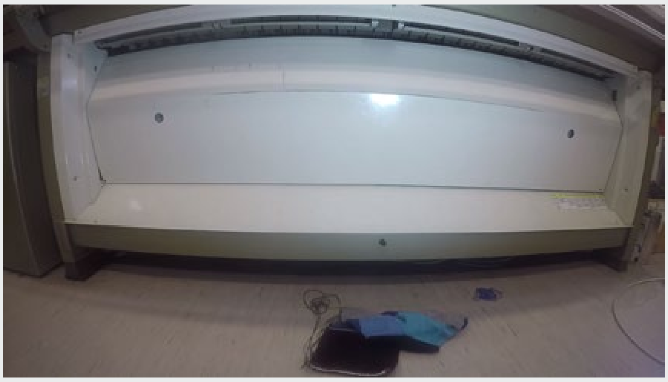


Carrier

Carriage and parallel needle beds



Binding off



Fabricated form

Figure 6.20
Programming and fabrication, video stills, 2018.

Process Mapping

As detailed previously in Chapter Five, Emergence of a Cubic Form-building System, the process-mapping diagrams emerged from sketches used throughout the design practice to support the mapping of 3-dimensional form onto the parallel front and back needle beds of the machinery. The final arrangement of these mappings at the exhibition (Figure 6.21) was an iterative, emergent process, as operatives and their processes were still being defined. Once established, the operatives and their corresponding icons[109] were added to the schematic to indicate the shaping component being referenced along each path. Further, this provided an explicit link to the cubic form-building domain diagram and the knitted artefacts themselves.

In this format, the diagram acts as a graphic flowchart or reference model, illustrating the 2-dimensional to 3-dimensional mapping in the programming of each operative, and the various translations and transitions required along the way.

While the mappings are intended to simplify these translations, WholeGarment's distinct fabrication environment remains a complex concept. As such, these mappings are one of the more technical components of the form-building system, essentially embodying the distinct construction technique from which the operative emerged. However, while it is not expected that all practitioners will have a firm grasp on fabrication, these mappings are also suggestive of programming sequence and highlight departure points for the integration of additional planes. As such, the mappings can also be used to communicate across domain boundaries for practitioners from outside the knit field.

At the time of exhibition some of the processes, such as + spiral, were not complete, while others such as + wedge represented geometries with multiple extensions rather than the integration of a cube base with a single operative. In addition, the pathway for each operative was not explicitly outlined, creating some ambiguity as to the intended route. Following the exhibition, modifications were made to the layout before being included in the form-building manual (Figure 6.21). Pathways for each operative were clearly outlined, including explicit reference to the stage of base cube fabrication at which the integration of the selected operative occurs. As such, this mapping can also be read as programming instructions, initialised with the base cube program and extended through integration of an operative's knit program.

Additional changes included each operative pathway being formatted into an individual page (Figure 6.22) and minor amendments to the graphic key. The language for describing process, programming and fabrication evolved through the process of documenting the design practice within this thesis. As a result, some of the language used in the mapping key was also revised to provide clarity and consistency between the graphic and detailed text in the thesis.

Figure 6.21
Process Mapping Diagrams, *Dimensions Unfolding* exhibition 2018 (above) and manual, Appendix A, 2019 (below).

Operative

+ wedge

Attributes

- triangular prism which can be integrated within the tubular knit or bias knit planes of cuboid fabrication

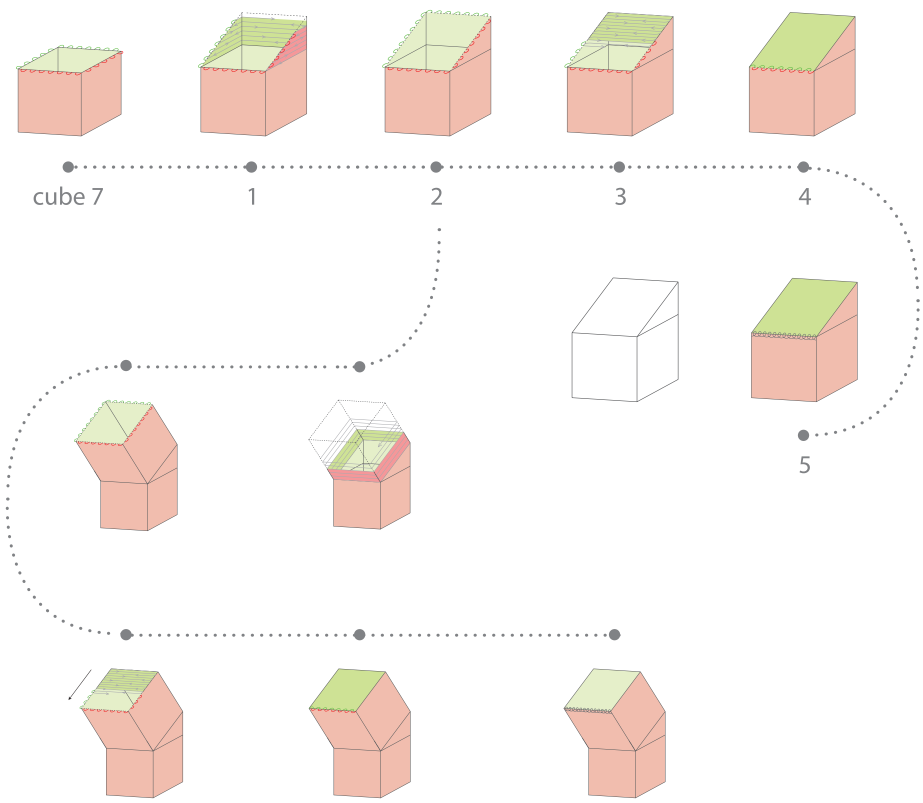
Compressed Program

Construction Notes

- flechage or short-row in tubular knitting
- knitted loops are added through additional courses of knitting
- can expand through bias knitting

Fabricated Form

Process Mapping



knit on front bed

knit on back bed

surface constructed on front bed

surface constructed on back bed

loop held on front bed

loop held on back bed

loop knitted on front bed

loop knitted on back bed

outline of intended form

outline of constructed form

direction of carriage

direction of surface construction

binding off

xii

Figure 6.22
+ wedge, Appendix A, 2019.

Summary

In this phase of the research, the process of consolidating practice findings for the purpose of exhibition revealed further insights and connections within the research. The exhibition itself was designed primarily to demonstrate the design practice underpinning the research, and to disseminate findings. Components included knitted artefacts resulting from the practice, documentation of design and fabrication processes, and a range of tools and graphic elements that form the foundation of a knitted form-building system.

The various components were further developed into a manual for knitted form-building fabrication in line with the underlying research aspiration to balance clarity and accessibility of process with representation of the full extent of 3-dimensional fabrication possibility for a wider design audience. As such, the manual and accompanying photographic catalogue of cubic geometries are intended to document and demonstrate 3-dimensional form-building capability to a range of practitioners; essentially anyone interested in the area of 3-dimensional knit fabrication. In this format, the manual represents key findings that have emerged from this research.

The following chapter discusses these findings within a broader context, alongside other conceptual insights that have emerged through the practice, highlighting the contributions of the research alongside limitations and future directions.

99 For example, it is intended that a hinge will be added from the last plane of a form, whereby the plane has closed or mostly closed the form. If two forms are joined before the last plane is fabricated, the forms are considered to be merged or integrated. In addition to the effect on the geometry, whether the last plane of a form is fabricated also impacts on potential geometry, in that differing edges or planes can be extended from as a result of a hinge, merge or integrate being applied. Most significant in this distinction is that the hinge is an independent programmable variable, while merge and integrate cannot be programmed as packages but are descriptors of the techniques used to combine two knit components. For further detail on these techniques see Appendix A.

100 Merge being the merging of two or more operatives to create a single programmed component and Integrate being sequential fabrication in which use of one operative follows the other.

101 Determination of the categories in which these artefacts are grouped is addressed in Chapter Five, Part 2, Operatives.

102 The development of icons as a visual notation for each operative is detailed in Chapter Five, Part 3, Attributes.

103 While these base forms are essential to the development of this series of geometries, it should be noted that the ability to fabricate cuboids was not a new finding within this research. However, the knitted artefacts in the remainder of the collection all result directly from findings within this PhD practice.

104 Boundary objects and look-and-feel prototypes are discussed in Chapter Four, Prototyping.

105 In compiling the catalogue, forms were evaluated against the documented form-building journey presented previously in this chapter. Though most forms remain consistent with their exhibition grouping, a small number have been reclassified due to their programming and fabrication resulting from multiple iterations of the extend cycle. For example, the bent cubic form (Figure 6.12) was originally grouped with + wedge. However, in following the form-building journey, it is seen that this geometric form results from a cuboid integrated with a wedge, which is then extended through another integration of an additional cuboid into a composition.

106 These images have been used throughout this text to illustrate elements of the practice, such as in Chapter Five, Part 3, in the investigation of cubic geometries.

107 'Waste' refers to the initial rows of knitting that ensure the fabrication is stable before construction of the intended form. Waste is knitted in such a way that it is easily removed from the form post fabrication.

'Yarn in' refers to the yarn being brought into the fabrication space to initialise fabrication.

'Tail' refers to the chain of knitted loops at the end of fabrication that allow the form to be released from the machine without unravelling.

Yarn in and tail are usually pulled through to the inside of a form post fabrication so these starting and finishing positions are not visible.

108 Optional stops were programmed into the form so that the machine was stopped at each significant change in knitting technique or package. Stopping the machine allowed for the yarn to be changed, so that each significant change in construction was indicated by a change in yarn colour.

109 See Chapter Five, Part 2, Operatives for a discussion on the development of operatives and their icons.

Chapter Seven

Conclusion

This research engaged in an exploratory design practice aimed at addressing a gap in knowledge around 3-dimensional form-building within the WholeGarment knit environment. Also considered throughout the design practice were mechanisms for easing engagement with the technology, for practitioners both within and outside of the textile domain. As such, guided by constructs of computational flexibility and performative form-building principles, the investigation led to the articulation and demonstration of a knitted cubic form-building domain and the generation of domain-specific operatives.

In the previous chapter, key findings emerging from the design practice were outlined, including distributable research artefacts in the format of a form-building manual (Appendix A) and a photographic catalogue of cubic geometric forms (Appendix B). In this chapter, areas of new knowledge and contributions to the field are highlighted. The chapter begins with a discussion of contributions in relation to the contextual and theoretical constructs framing the research. The following section addresses a key limitation of the study concerning the repositioning of the technology into a broader non-garment domain, which led to the identification of two significant areas for further research.

Some additional limitations emerging from specific areas of the practice are also addressed in the chapter. The design practice revealed numerous concepts and paths that remained unexplored and which would warrant future investigation in order to expand form-building possibility or to further validate findings. As such, areas of research that show strong potential to progress and demonstrate WholeGarment technology's advanced form-building capability and support a repositioning as an additive manufacturing textile fabrication tool are noted throughout. A short summary of the research completes the chapter.

Reflections and Contribution

Central to the contribution made through this research is the recognition and articulation of an emergent design dimension in 3-dimensional knitted form. Alongside this, the research findings provide access and greater understanding of seamless knit technology's – or specifically in this research, WholeGarment's – advanced fabrication capability to a broad range of design practitioners. The following discussion addresses the significance of the research contributions, both for the knitted-textiles field, and in relation to the suggested repositioning of WholeGarment technology within a broader design and manufacturing environment. As such, the section draws from the research objectives outlined in Chapter One and the contextual framing of Chapter Three, providing a discussion of the form-building methodology emerging from this research and the alternative systems of use that underpin its adoption. The cubic form-building domain that was established through this research is also addressed.

A 3-Dimensional Knitted Form-building Methodology

The form-building methodology consist of a form-building development journey detailed in Chapter Six, and a form-building system, detailed in Chapter Five, Part 2, offering an alternative means of engaging with the fabrication of knitted form within the WholeGarment environment. Significant to this approach is the use of performative operatives; additive fabrication categories that represent distinct components of knitted forms. These components can be merged or integrated in varying combinations to generate 3-dimensional knitted forms. In depicting 3-dimensional form in this component format, the methodology is intended to dissuade design fixation and encourage innovative exploration, such that the creative capability of the technology is no longer masked behind established methods of form building.[110] Further, the methodology is intended as an expanding and evolving framework, with operatives presented as components of a library, allowing for the library to be further populated as the domain is explored.

In developing the format and components of the methodology, consideration was also given to supporting access and understanding for practitioners, both within the knitted-textiles field and outside of it, thus accommodating a repositioning of the technology as a truly 3-dimensional fabrication tool accessible to a broader design domain. As noted in Chapters Two and Six, it is not expected that all practitioners will engage with all components of the methodology, but that, in combination, the components provide insight into some of the varied design and programming elements within the WholeGarment environment.

Of note, while the methodology is positioned to allow continued exploration and development of 3-dimensional knitted form by a range of practitioners, it has not been evaluated outside of this practice – an aspect addressed further in Limitations, later in this chapter. Further, the methodology, and in particular the form-building development journey, does not encompass a mechanism for assessing feasibility, and as such relies on the fabrication knowledge of an experienced knit practitioner; an aspect that has the potential to frustrate and deter engagement with the technology.[111]

In this regard, it is assumed that for many practitioners the intensive investment of time required to engage with WholeGarment's design and programming interface is not viable. Rather, it is assumed that design practitioners would work with an experienced knit practitioner to realise intended outcomes. In this regard, the manual aims to provide enough information that practitioners can engage with the design possibility of WholeGarment technology without being overwhelmed by the specialist knit environment or technical details. Similarly, the more technical elements of the system, such as process mappings, are formatted to provide an indication of technique rather than detailed programming instructions, allowing knit practitioners a base from which to explore form-building methods.

Articulation, Demonstration and Cubic Form-building Process

A key objective of the research was the investigation and demonstration of non-garment knitted form-building. In addressing this objective through an exploratory practice, a cubic form-building domain was established. Initially, the research was focused on demonstration of possibility within this domain, and the development of tools to support further exploration and application. However, as the research advanced it became apparent that notions of language and representation required further consideration to enable greater accessibility to the geometric shaping within this domain. More specifically, the lack of a language for 3-dimensional form, either visual or textual, was problematic for conceptualising and communicating design, even within this self-directed research.

As outlined in Chapter Six, Articulation, this lack of language prompted the development of diagrammatic and symbolic representations to describe these new cubic textile geometries. The intrinsic difficulty in communicating information around knitted textiles was noted In Chapter Three, Language of 3-Dimensional Knitted Form. Of note, with regards to non-garment application, was Underwood's (2009) comment on the need for a means of communication that is not too technical or domain specific. The format of the representations developed in this research are intended to provide greater ease of access to the form-building domain for a general design practitioner, while illustrating the performative operative through which knitted forms materialise.

In addition to articulation is the demonstration of 3-dimensional cubic form-building potential provided by the artefacts fabricated through practice. The presentation of the artefacts as relatively neutral forms allows for suggestion and user-interpretation, and also serves to support their role as learning resources and boundary objects. As learning resources, the tangible and material properties of the artefacts provide a physical form for evaluation and reflection. In the role of boundary objects, the artefacts provide visual cues which, in inhabiting a 3-dimensional space, can be easily read as design prompts across a range of design and manufacturing domains.

Encompassing articulation and demonstration are the form-building manual (Appendix A) and photographic catalogue (Appendix B), outlined in Chapter Six. The components of the manual encompass the research findings, including the form-building methodology and a range of tools and resources to support understanding and engagement with the cubic form-building process. The photographic catalogue, while not as tangible as the physical artefacts, still provides evidence of possibility in an easily understood format. In the Interdisciplinary Projects outlined in Chapter Five, Part 1, the lack of mechanisms for communicating form-building potential was noted to constrain innovative development of non-garment products. In such situations the photographic catalogue could prove invaluable. Further, as with other emergent fields such as 3-dimensional printing, the subsequent proliferation and visibility of forms is expected to encourage further exploration of the technology's capability, allowing for ideation by a wider range of practitioners.

Extending the Space of Possible Design

In articulating and demonstrating an emergent knitted form-building domain, the research is seen to extend the design space beyond known precedents, as detailed in Gero's (1990) space of possible designs in Chapter Three. Essentially, evidence of this cubic form-building capability provides a new way of thinking about 3-dimensional knitted form, adding support for the transition and application of knitted cloth away from niche knitwear areas into a broader design domain.

Writing of the system of categorising against a norm, as identified in prototype theory, Silve (2006, p. 3) notes that "new objects joining the category will subsequently affect the norm of the category against which further objects will be judged, and it is through this continued process that the norm slowly evolves." In this research, as the practice advanced and further possibility was revealed, the parameters of the domain, while being further defined by the research, were also perceived to be further expanding. Gero (1990, p. 28) notes that design has two contexts, "the context within which the designer operates and the context produced by the developing design itself.... The context shifts as the designer's perceptions change."

Thus, this research has identified and demonstrated a small area of 3-dimensional form-building capability, subsequently framed as a knitted cubic form-building domain. While this has incited a shift in the norm, it is through the continued exploration of WholeGarment's advanced form-building capability that the space of possibility will be significantly extended. In this regard, emerging from technical findings documented throughout Chapter Five are several areas that show strong potential with regard to further extending the proven potential of seamless knit technology's distinct form-building capability. The areas highlighted below stem from insights throughout the practice, not just those emerging from the primary research path, and, as such, do not relate exclusively to cubic geometric forms.

Hinges or Joins

The concept of hinges or joins as a variable in 3-dimensional form-building first emerged through the rapid prototyping of experimental cubic forms detailed in Chapter Five, Part 1. This part of the practice included an exploration of variables that could be altered within a join to embed further shaping into the 3-dimensional forms or, more specifically, the directional forces within their geometry. However, when this variable was revisited in the investigation of cubic geometries in Chapter Five, Part 3, just one variation was used. That is, the forms fabricated under the + hinge operative were constructed using a short interlock join between geometric components. In the development of non-garment forms, it is expected that the flexibility and variation this component offers could play a significant role, particularly in areas of application where repeats or tessellations are required. Further, the integration of technical yarns to create degrees of stability or rigidity within the hinge provides further potential for varying design applications.

Widening and Narrowing

The range of forms presented in the + swell & taper category utilised inside widening and narrowing techniques in their construction. While this was adequate for the demonstration of capability and for supporting the emergence of a new operative category, the directional forces this introduced to the form were not fully resolved. Further investigation in this area would allow for a more accurate positioning of shaping lines within a geometric form. In addition, exploration of alternative widening and narrowing techniques, such as parachute shaping, are likely to support the fabrication of a broader range of derivative geometric forms within this category.

Additional Carriers

Also emerging from the investigation of geometric forms in the + swell & taper category, but relevant across the broader cubic form-building domain, is the introduction of additional carriers within a fabrication. Essentially, an additional carrier represents potential for additional planes or additional surface area within a form. However, as for garment production, complexity in this process arises from constraints around the necessary integrations of distinct planes, and the programming required for sequence and separation of carriers so that adjacent planes or geometric forms are not inadvertently closed or joined. That said, the potential of additional carriers to vastly alter and extend the parameters of the 3-dimensional form-building domain is such that further investigation in this area would be of significant value.

Potential for 4-Dimensional Knit Fabrication

The fabrication of forms in 1/4 gauge emerged as a finding from the investigation of knit as a topological surface, detailed in Chapter Five, Part 1, whereby it was demonstrated that with 1/4-gauge construction and the introduction of additional carriers, four layers of cloth could be fabricated as two independent tubes. While time constraints restricted further investigation, conceptually, this finding suggests the potential for multi-layered form-building. For example, in the investigation of + ledge geometric forms (Chapter Five, Part 3), a number of design concepts were left unrealised due to the need for all or part of their form being reliant on four layers being fabricated simultaneously. The capability to knit geometric forms at 1/4 gauge would allow for a layering of forms such that cubes could be constructed within the bounds of another cube. Though I have not thoroughly unpacked such geometric forms, in the instance of any being considered feasible, an extensive amount of programming would be required with particular attention given to knit and carrier sequences. However, further research in this area and the realisation of such forms has the potential to significantly alter our perception of knitted form-building, essentially introducing another dimension to the domain of 3-dimensional knitted form-building.

Topological Surfaces

The exploration of topological surfaces (Chapter Five, Part 1) was not pursued past preliminary findings as the practice was taken in an alternative direction. However, there remains significant potential in exploring this area as a means of expanding and extending the knitted form-building domain. Notably, the uninterrupted surfaces of topological forms offer an alternative perspective to form building; one that would seem well aligned with the seamless construction of WholeGarment knit technology.

Extending the Library of Form-building Operatives

Underpinning further investigation of form-building capability is the notion that this has the potential to reveal additional form-building operatives. For example, introducing additional carriers to create branches within a geometric form, or quarter gauging construction to allow fabrication of 4-dimensional cubes, would potentially lead to the determination of further operatives for the cubic form-building domain.

This concept of an expanding library of operatives is encompassed within the form-building methodology presented earlier in this section. In addition to the potential for further cubic operatives, an expanding library also allows for the addition of non-cubic geometric categories and their form-building components. For example, the geometric forms such as cones and domes presented in Underwood's (2009) research could be deconstructed into form-building components or operatives. In addition, investigation of geometries such as spheres would similarly allow for the generation of new operatives. As was demonstrated throughout Chapter Five, and particularly in Part 3, the identification of each new operative, and its corresponding construction techniques, not only resulted in the design and fabrication of an extensive range of derivatives, but also improved understanding of the fabrication environment in such a way that unresolved geometric forms could be revisited, and geometries not previously considered could be explored.

In this context, determination of further form-building operatives will support population and demonstration of WholeGarment technology's advanced 3-dimensional fabrication capability. In turn, this is expected to encourage increased use of knitted cloth in diverse design applications and would therefore contribute not only to the expansion of the library of operatives, but also to the broader research field.

Alternative Systems of Use

With regard to the form-building methodology outlined in the previous section, the research additionally considered alternative systems of use in comparison to the current constrained application of WholeGarment technology. In Chapter Three, it was noted that current use was highly influenced by the arrangement of the technology's design software and specifically the cultural practices of the industrial knitwear setting that are embedded within this interface. Of particular significance to this research was that the format of this system essentially masked the 3-dimensional form-building capability of the technology.

This research was grounded in a conceptual repositioning, or adoption of an alternative technical code, subsequently demonstrating further secondary instrumentalisation of the technology. While the attributes of this alternative code were effective for this study, underpinning the form-building methodology discussed in the previous section is the framing of yet another system. Drawing from the contextual constructs in Chapter Three around practitioner knowledge and form-building approaches, the following discussion further articulates the framing of these alternative systems of use.

Practitioner

In Chapter Three, Knitted Textile Practitioner, consideration was given to frameworks of knowledge that would support practitioner engagement in the context of an exploratory study to define and extend an ill-defined fabrication domain. In this regard, constructs around computational flexibility, understanding of fabrication, and design fixation were outlined, all of which were shown to effectively support the exploration of form-building capability within the WholeGarment environment (documented in Chapter Five). However, it is not expected that these attributes or areas of knowledge are necessary for a broader practitioner engagement with the technology. The methodology emerging from this research is intended for practitioners from a range of backgrounds and skill levels, and as such implies a system of use that spans domain boundaries. In this context, application of the methodology is not reliant on domain-specific knowledge or technical knit-programming skill but, as previously stated, is reliant on engagement with a skilled knit practitioner to complete the journey from design concept to fabricated form.

With consideration for the knitted-textile practitioner within such a system, and recognising the vast capability encompassed within the WholeGarment environment, the potential for fluidity and specialisations in practitioner roles is revisited. This need not be in the industrial roles of the traditional designer and technician specialisations, but allows for increasing variation in areas of expertise as the application of knitted cloth is extended into new domains. The WholeGarment design system supports such a fluidity; having all its form-building capability encompassed in a single interface or, more specifically, a programming grid. In this format, increasing levels of skill and understanding are easily accommodated within an interface that is accessible to all users. This transition of knowledge and subsequent access to capability was documented throughout Chapter Five, whereby increasing programming and construction knowledge led to the investigation of fabrication principles such as racking, widening and narrowing, and, subsequently, the emergence of additional cubic form-building operatives.

Approaches to Knitted Form-building

Also significant in the system of use surrounding the methodology presented in this research is that this system, and its associated tools and resources, are not intended as a stand-alone guide for accessing 3-dimensional knitted form-building. Rather, they are presented as accessible resources that can be used or considered, alongside other areas of research and development in the field. In Chapter Three, the lack of a 3-dimensional interface or representation within the WholeGarment environment identified a number of form-building approaches. This included CAD software, Underwood's (2009) Package Adaptation System and Carnegie Mellon Textiles Lab's Knit Compiler. While these systems were not considered suitable, or were not accessible, for this exploratory investigation, they provide invaluable resources in supporting a broader engagement with WholeGarment technology and its potential.

To explain further, given the many variables embedded within the construction of 3-dimensional knitted forms it is expected that a range of systems and frameworks will be required to provide comprehensive support for 3-dimensional knit design and fabrication. The means by which the methodology presented in this research might conceptually integrate with other systems of form-building is addressed briefly below. In acknowledging the potential of these systems to work alongside each other, the discussion also recognises that such consideration reveals areas for further research.

Firstly, in relation to CAD software, the 3-dimensional modelling of surfaces would allow a digital template or interface for the process mappings that were undertaken in this research. As documented in Chapter Five, Part 3, these mappings provide a visual guide for the programming of forms, while also allowing for the feasibility of designs to be evaluated. One of the constraints of these mappings, related to their sketching within the Shima Seiki design system, is that this did not allow for iterative development and testing[112] – a constraint that is easily addressed with the layering of design attributes incorporated in most CAD software.

As a commonly used and easily accessible tool, CAD software would allow for design and conceptualisation of knitted form, and for feasibility testing outside of the proprietary knit software, without the need for intensive programming. Of note, feasibility could only be determined with fabrication knowledge. However, CAD's 3-dimensional models also allow for knowledge sharing across domains, essentially providing a 3-dimensional digital template for communicating and unpacking the complex translations between form and the programming and construction of knitted form. Further, with the translation of 3-dimensional form to programming of needle beds shown to reveal unexpected possibilities on several occasions throughout this practice, participation in feasibility testing by a range of practitioners has the potential to further extend the perceived constraints of knitted form-building, and presents another area for further research.

Also addressing the unpacking of knitted planes is the Knit Compiler research project at Carnegie Mellon Textiles Lab. While this software is not accessible in the public domain, it would be beneficial to understand its effectiveness with regard to perpendicular planes and geometric form. As a tool for translating a 3-dimensional mesh or surface into a knit program, it could also support feasibility testing of design concepts. Use of such an interface would likely require the support of a range of resources, such as those emerging from this research, in order to fully understand and demonstrate the advanced fabrication capability of WholeGarment technology.

Another area of significance in knitted form-building is that of the parametric constraints related to knitted geometric forms in a fabrication environment with discrete needle and stitch movements; a concept addressed in Underwood's (2009) Package Adaptation System. In this research, the parametric constraints of cubic form-building were considered in Chapter Five, Part 2, as the practice sought to adapt an existing cubic geometric form according to specific dimensions and orientations. While these adaptations were determined manually in this research, building on Underwood's (2009) system to include formal representation and programming instructions for cubic geometric forms would be particularly beneficial in supporting the application of cubic forms in non-garment product development.

Further, integrating this parametric system with the mapping of planes in CAD software would allow parametric constraints to be applied to 3-dimensional representations of geometric forms in such a way that the unpacking of planes could be translated directly into programming dimensions or, more specifically, wales and courses.

Returning to the concept of alternative systems of use, this research considers two systems. The first, underpinned by expert programming and domain knowledge, and an operative form-building approach, led to the emergence and articulation of a knitted cubic form-building domain and associated methodology, systems and tools. In contrast, the second is grounded in a wider level of practitioner engagement, across domain boundaries, with a focus on the development of non-garment knitted-textile products. The effectiveness of this second system of use is yet to be evaluated, and, as such, is addressed in the following section on limitations, and provides another area for further research.

Limitations and Future Directions

The repositioning of WholeGarment technology proposed within this research is in part motivated by the increasing evidence of its advanced fabrication capability, which could be used in innovative, value-adding solutions across new areas of application outside of the textile domain. However, it is also in reference to this repositioning that the primary limitation of this research emerges. That is, there is potential for a disconnect between a methodology and form-building manual derived from self-directed practice, and its proposed use to support engagement with WholeGarment technology across a broad range of practitioners from varying domains. To explain further, while the manual and its components were discussed with colleagues throughout, and I was able to iteratively evaluate and reflect on its tools as the practice advanced, it has not been evaluated or tested outside of this design practice.

Though emerging from self-directed practice, the integrity of the methodology and form-building manual is supported through various engagements within the research. Firstly, the interdisciplinary projects in the preliminary studies of this research (Chapter Five, Part 1) allowed for insight into the difficulties surrounding non-knit practitioner engagement with the specialist WholeGarment knit environment. More specifically, the complexity of an unfamiliar fabrication environment and lack of a visual representation within WholeGarment's design system, or demonstration in fabricated form, left practitioners with limited means through which design concepts could be considered or suggested. In addition was the insight afforded by my own experience of the WholeGarment knit environment. With the digital knit environment – and specifically the programming interface – as my entry into the knitted-textiles field, I was able to draw from personal experience with regard to the complexity of engaging with a seemingly abstract translation between code and cloth, as is often the case for non-knit practitioners. And, having no background in 3-dimensional form-building, the challenges I encountered in navigating the relationship between parallel needle beds and 3-dimensional fabricated form are likely to be comparable to those experienced by other practitioners.

Writing of research conducted through design practice, Boess (2009, p. 4541) notes, "the knowledge that is produced, need not necessarily be exact and proven. It is more important that it creates a scenario, a possibility." In this research, the methodology and manual create such a scenario or possibility, related to non-garment, knitted cubic form-building, rather than a formalised system. The testing and evaluation by external practitioners presents an area for further research, addressed in more detail below.

An additional limitation with regard to the repositioning of WholeGarment technology into a broader design and manufacturing domain is that the research does not include consideration for, or draw from experience with, the differing attributes of form building and application in other design domains. For example, in comparison to the knitted-textiles domain and the application of knitted cloth in garment and accessories, aspects such as materials or substrates, scale and design methods are likely to differ in domains such as industrial design and architecture.

While there has been some research into the material interactions and structural considerations of using knitted cloth in other design domains,[113] the area remains largely unexplored. Furthermore, this issue was not specifically addressed within the scope of this study. In this regard, the repositioning of WholeGarment technology as a 3-dimensional fabrication tool is a conceptual consideration in the belief that the potential for 3-dimensional knitted form will continue to grow alongside advances in fibre and technology, and the subsequent exploration and research of various applications. As for 3-dimensional printing, in which attributes such as substrate and scale continue to be expanded, and application is subsequently extended into new domains, increasing the application of 3-dimensional knitted form is expected to prompt technological developments that incorporate the needs of other design domains. Identifying such needs highlights another area for further research, addressed in more detail below.

Engaging Practitioners from Other Fields in Non-garment Product Development

As noted in the previous section, though intended to engage a broader range of practitioners, the form-building manual and photographic catalogue that have emerged from this research have not been evaluated outside of my own practice. Further, there is limited evidence to support the application of knitted geometric forms in innovative, value-added, design outcomes. Kettley (2007, p. 5) notes that critical design recognises “the cultural roles of artefacts beyond their technological function, and in the case of novel computational technologies, there is a need to examine and critique the trend for innovation as an end in itself.” While there has been some demonstration of non-garment application in commercially focused orientations, the recent revision by Shima Seiki to include home furnishing, automotive and aeronautical among their advertised markets (Shima Seiki, 2019a) perhaps shows the strongest recognition to date for the design possibilities through transition of knitted cloth into fields and applications outside of knitwear.

The interdisciplinary projects detailed in Chapter Five, Part 1, engaged practitioners from other fields as a means to shift knitted form-building and the application of knitted cloth from its traditional knitwear setting. However, a lack of understanding and demonstration of WholeGarment technology’s fabrication capability was seen to inhibit the level of engagement of non-knit practitioners. In this regard, the expectation remains that engagement of experts from other fields, such as textile scientists and industrial designers, would support the extension of 3-dimensional knitted geometries into new forms and functions, both through contribution of their own expertise, and in their lack of design fixation within the WholeGarment knit environment. In the setting of interdisciplinary projects, such engagement would also allow for the methodology developed in this research to be evaluated with regard to its effectiveness in establishing shared understanding and supporting the communication of knitted form-building principles across disciplines.

Application of Knitted Cloth in Non-garment Products

Also identified in the previous section as an area for further inquiry is the consideration of material properties and interactions in using knitted cloth in non-garment products. Outlined below are three areas for consideration, which emerged from the preliminary studies described in Chapter Five, Part 1.

Technical Knitting and Technical Yarns

The application of knitted cloth in non-garment products is expected to use technical yarns with greater durability and functionality than would be used in traditional knitwear and accessories. Further, in fabricating textile forms that are not intended for the body, it is expected that considerably reduced tolerances would be accepted. In this regard, though 3-dimensional form-building capability has been demonstrated, its benefit to a broader design domain is likely to rely on the integration of advanced yarns and technical-knitting[114] expertise. While research into the properties of various technical and functional fibres is available, it is the compatibility of fibres with 3-dimensional fabrication techniques and the structural integrity within the stitches of knitted cloth that are of significance to the development of non-garment products. To date, such research is largely contained within commercial development or research and development labs. Alongside this factor is the limited availability of technical yarns, due to commercial restraints or cost, resulting in a lack of accessible knowledge in this area. Consequently, documentation of the properties and processes of integrating technical yarn and technical knitting with the fabrication of 3-dimensional knitted forms would provide a valuable resource for advancing non-garment product development.

Frames and Fills

In addition to the range of functionality embedded within knitted cloth through technical knitting and technical yarns, is the change to interactions with the cloth. While knitted garments are most often considered in relation to the body, interactions in non-garment forms are likely to be with frames or fills. For example, in the interdisciplinary projects discussed in Chapter Five, Part 1, aspects such as openings and fastenings for accommodating frames and fills, and the interplay between these elements and the knitted cloth, were identified as areas of the projects that were not adequately resolved. The design concepts used in these projects were most often derived from garment construction, such as buttonholes, and did not offer the stability and durability non-garment products are likely to require. Alongside technical knitting knowledge and the use of technical yarns, it is expected that expertise from other fields such as industrial design would support further development in this area.

Extending from this is the interaction between the material of intended fills and frames, and the knitted cloth, or textile skin, that surrounds them. To explain further, as the functionality and technical attributes of knitted cloth become a key element of product developments, there will be an increasing need for understanding of the characteristics of the cloth and the means by which it is integrated into, and reacts with, other components of the product.

Haptic and Visual Aesthetic

Also evident in the interdisciplinary projects in Chapter Five, Part 1, was the desire for haptic and visual aesthetic expression within the textile surfaces of non-garment forms. Though WholeGarment knitwear is often noted as being constrained in texture and patterning, possibility within this area has been shown by design outcomes in Kalyanji (2013) and Smith, Kalyanji and Fraser (2014). As knitted cloth transitions into alternative areas of application, further investigation of haptic and visual aesthetic possibilities within the parameters of seamless knit construction should prove beneficial for both garment and non-garment application.

Summary

Seamless knit technology was introduced 25 years ago, yet exploration of its 3-dimensional form-building capability remains limited, with little research available in the public domain. A distinct digital fabrication environment positioned largely within industrial knitwear manufacture and the numerous variables embedded within the seamless fabrication of knitted form contribute to the complexity surrounding design and application of the technology's advanced fabrication capability. As a result, the 3-dimensional knitted form-building domain is largely undefined. Further constraining access to this capability is a lack of form-building approaches that cater to the distinct fabrication environment.

Alongside this, the rapid and continuous development of knittable fibres has led to the form and function of knitted cloth being extended into unfamiliar domains. The role WholeGarment technology can play in this transition, and its potential for value-added design outcomes, is becoming more evident. As such, this research was centred around investigation and demonstration of 3-dimensional knitted geometric form, with the objective of engaging a broader range of design practitioners in the WholeGarment knit environment. More specifically, the research documented in this text and the discussions throughout represent a practice-led investigation of WholeGarment technology's latent 3-dimensional form-building capability.

In this endeavour the practice was underpinned by a conceptual repositioning of WholeGarment technology, away from its intended application in knitwear manufacture and the associated industry practices embedded within the technology's design system, to a design domain grounded in notions of 3-dimensionality, volumetric forms and tactile surfaces. Further underlying this repositioning was a consideration for alternative systems of use. The system of use adopted for this study was defined by a digital making practice, framed by constructs of computational flexibility, performative form-building principles and non-garment knitted form; essentially establishing an alternative technical code for engagement with WholeGarment technology's advanced fabrication capability.

As the research advanced through exploratory phases of practice, the unpacking of a cubic geometry revealed a new perspective and understanding of the additive fabrication principles of 3-dimensional knitted form, through a connective charting between 3-dimensional geometries and the parallel needle beds of their construction. Significantly, this prompted consideration of knitted planes bounding a volume, and subsequently exposed the possibility of remapping these planes in alternative configurations. The systematic phases of investigation that followed led to the emergence and articulation of a knitted cubic form-building domain that included identification of domain-specific form-building operatives that accommodate the distinct additive fabrication principles of digital seamless flatbed knitting.

Alongside this, the iterative development of form-building tools throughout the practice informed a cubic form-building system incorporating operatives, textual and visual articulations, and process mappings to support the translation of 3-dimensional geometric design concepts into knit programs and, subsequently, fabricated forms. As such, the practice yields multiple and varied contributions to the field of knitted textile form-building. For example, the 3-dimensional cubic artefacts resulting from the practice extend the proven demonstration of WholeGarment's advanced fabrication capability in the form of easily decipherable objects.

In addition, the research offers a methodology that encompasses a new perspective for thinking about knitted form within an alternative system of use. Comprised of a form-building journey, and form-building system, the methodology presents a generative design strategy structured around a library of operative form-building components that can be combined in various ways. Returning to the underlying motivation to support and ease the extension of knitted cloth into a broader design and manufacturing domain, the methodology invites engagement from both knit and non-knit practitioners; essentially any practitioner seeking to further explore WholeGarment technology's 3-dimensional fabrication potential. Further, the methodology is supported by a range of tools and resources, encompassing both conceptual and technical design principles, to support the integration of 3-dimensional knitted form-building knowledge into current design practice.

Sullivan (2009, p. 62) notes that one of the goals of design research is to "provoke individuals and communities into seeing and understanding things in new ways." In a language and form more common to domains such as industrial design and engineering, the combination of cubic artefacts, domain articulation and form-building methodology emerging from this research provides an alternative perspective of 3-dimensional knit fabrication and, in addition, allows for the technology's 3-dimensional form-building capability to be accessed by a broader range of practitioners and applied in significantly different ways. In this context, just as WholeGarment technology resulted from radical technological innovation, the technology has the potential to radically shift the form and application of knitted cloth, and the knitted textiles field, into a broader design and manufacturing domain whereby its distinct fabrication capability can be exploited in innovative design solutions.

110 As has been the case with the knitted-garment templates of WholeGarment's automatic software interface.

111 To explain further, while each operative component can be fabricated individually, and there are numerous combinations that could emerge from the form-building journey, there is also potential for these combinations to be unfeasible, due to the additive fabrication principles of knitted surfaces.

112 Constraints of process mappings and feasibility testing in the conceptualisation of 3-dimensional knitted geometric forms are identified in Chapter Five, Part 3.

113 For example, the Knit Architectures and Morphable Architectures projects at Taubman College, Ann Arbor, Michigan, investigate the potential of machine knitting architectural materials and transformable architectural systems, and include consideration for various material properties (https://taubmancollege.umich.edu/research/research-through-making). Another example is the Isoropia project at CITA (Centre for Information Technology and Architecture), Copenhagen, in which knitted textiles are embedded with active bent-fiber-glass rods to enable a lighter architecture in which material behaviours are balanced to build smarter with less (https://kadk.dk/en/case/isoropia).

114 A brief discussion on technical knitting is provided in Chapter Two.

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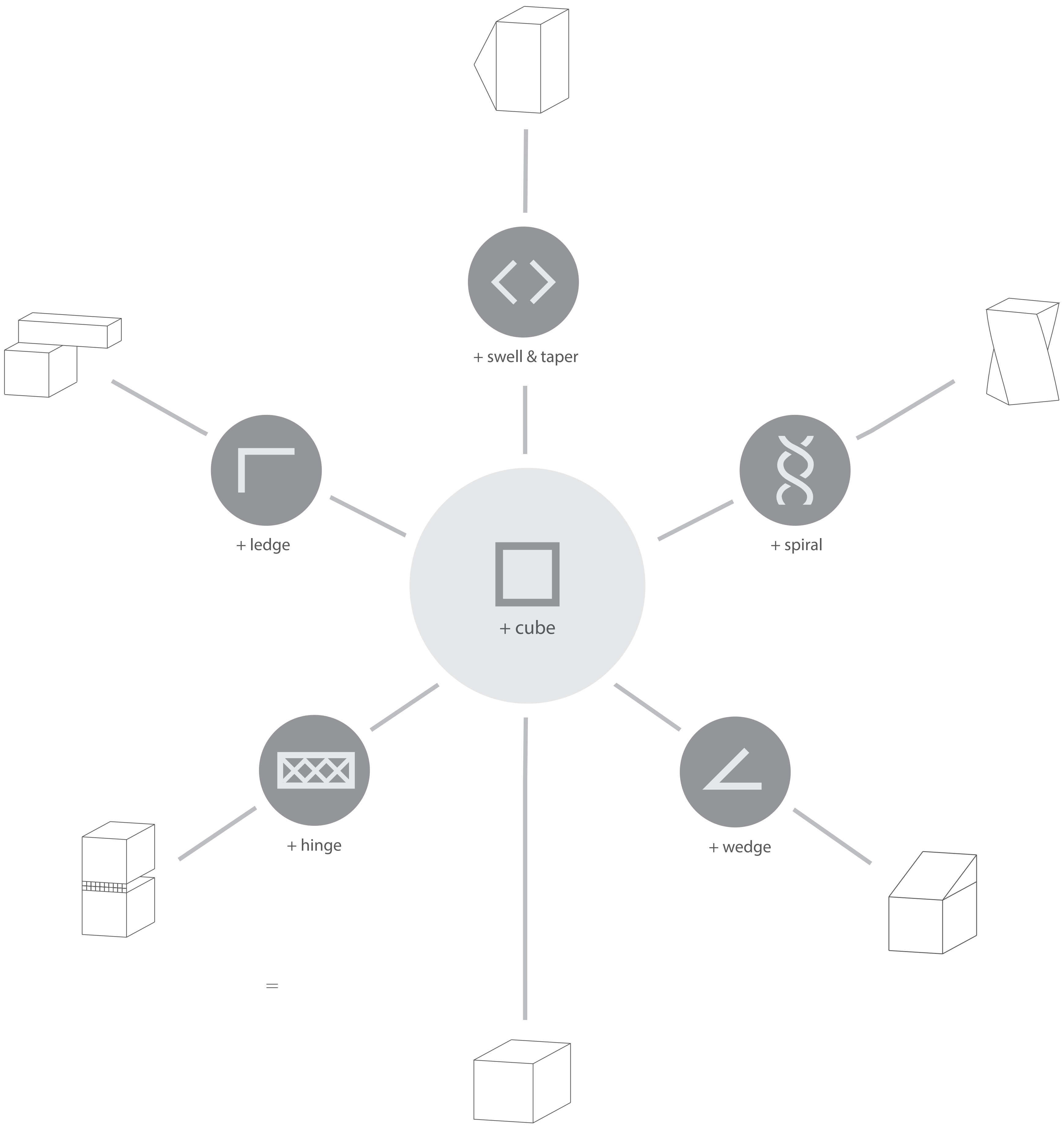
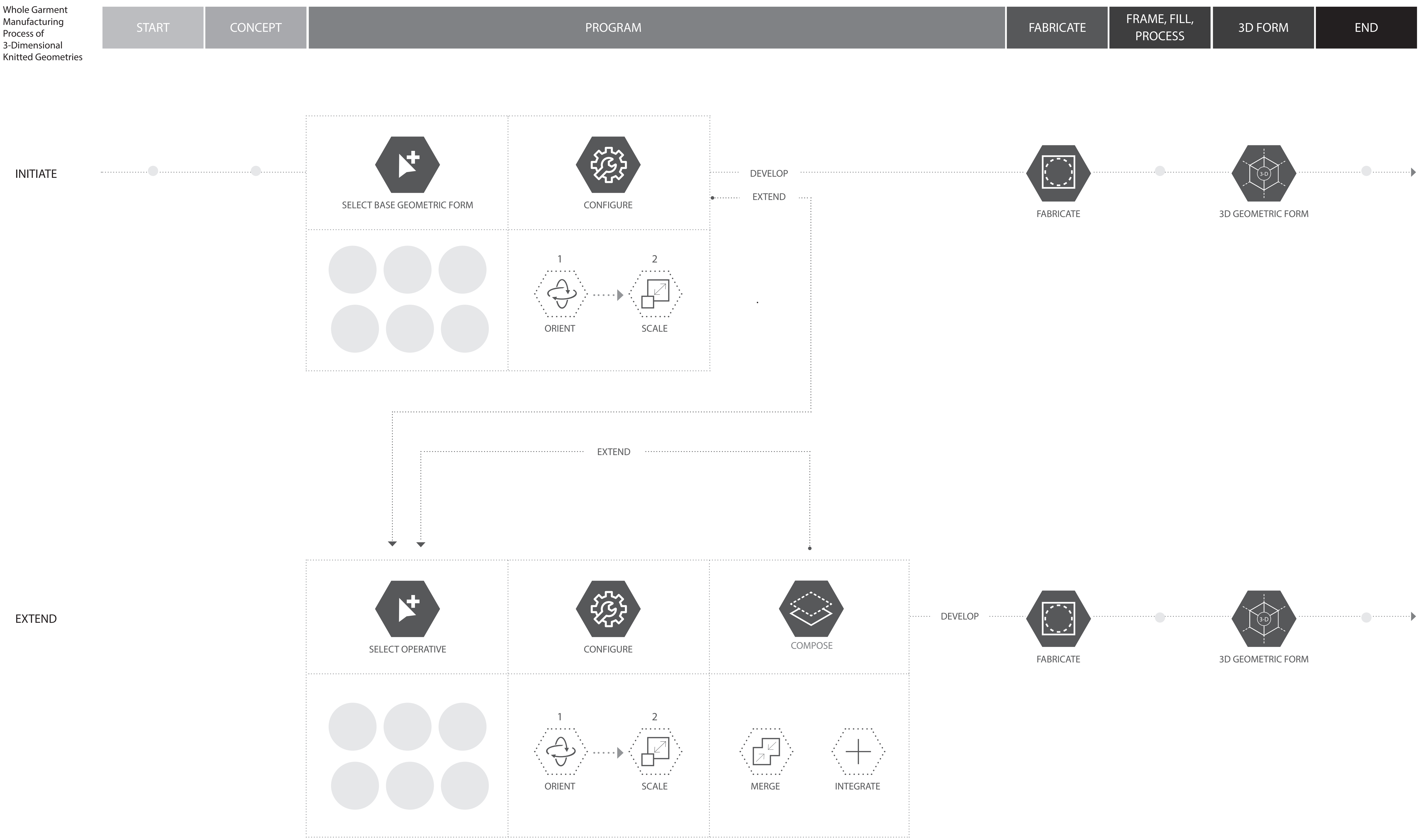
Appendix A
Dimensions Unfolding: Manual of 3-dimensional Cubic Form-building

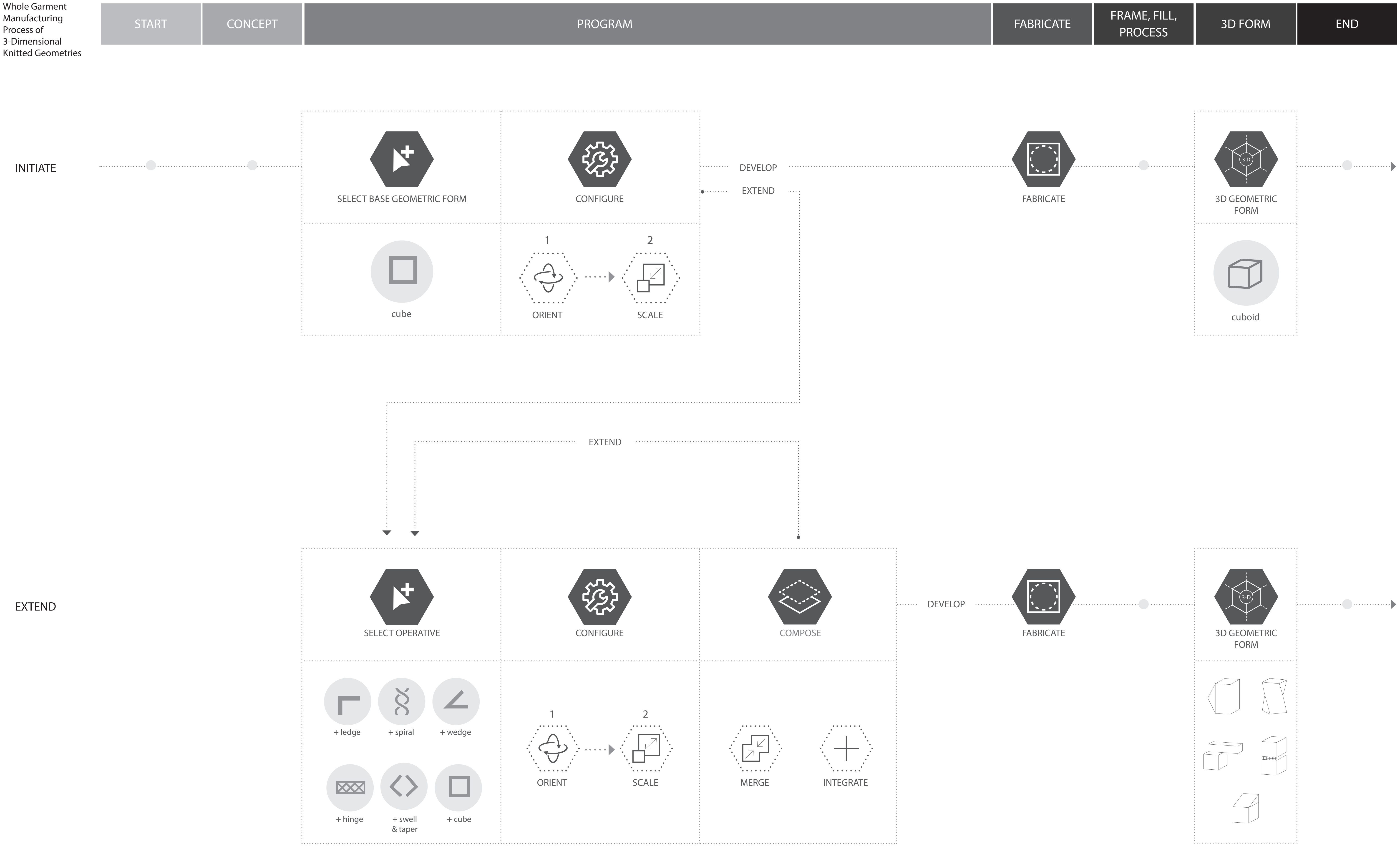
Knitted 3-Dimensional Cubic Form-building Domain



Form-building Journey of 3-Dimensional Knitted Geometric Forms

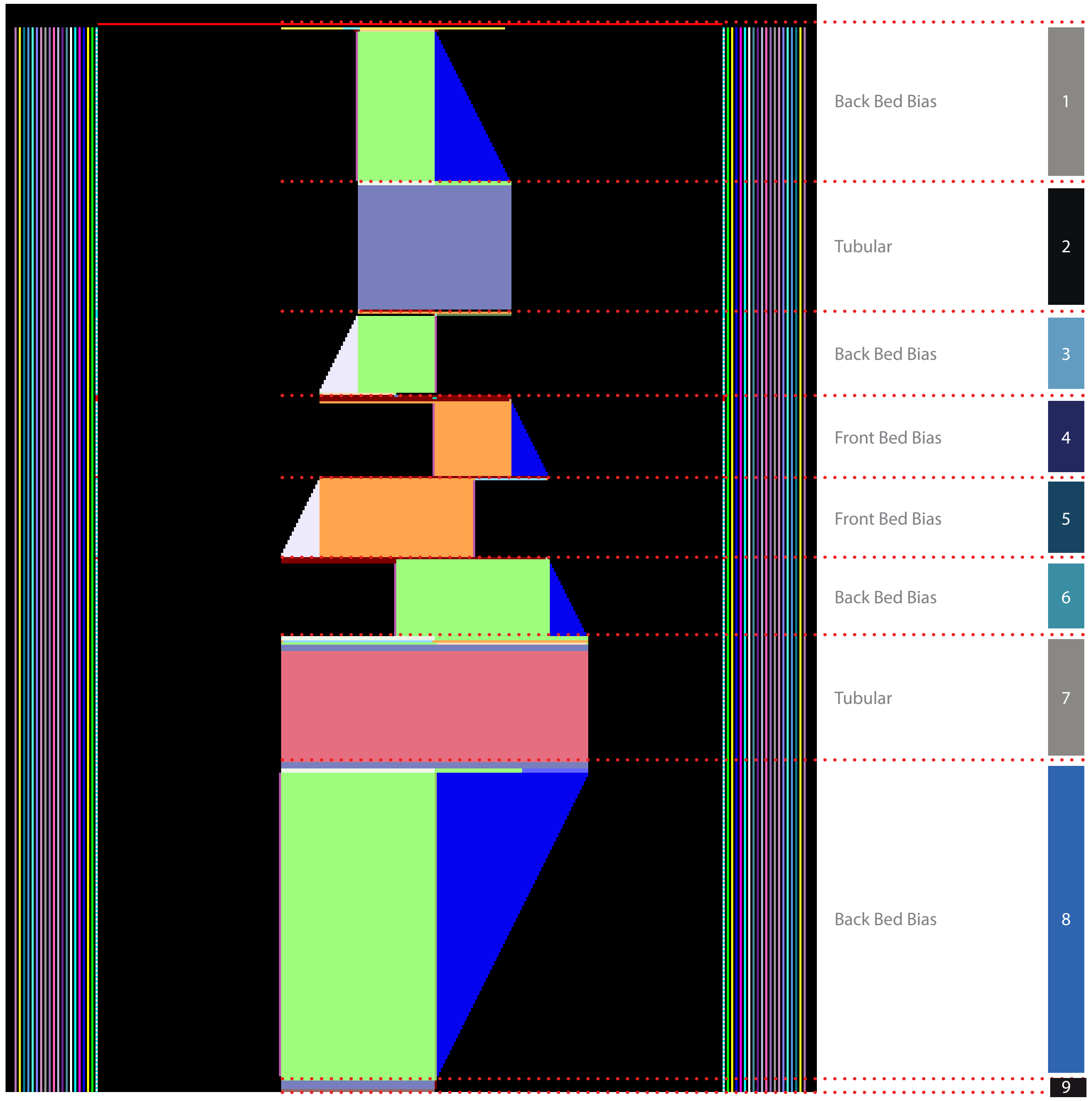


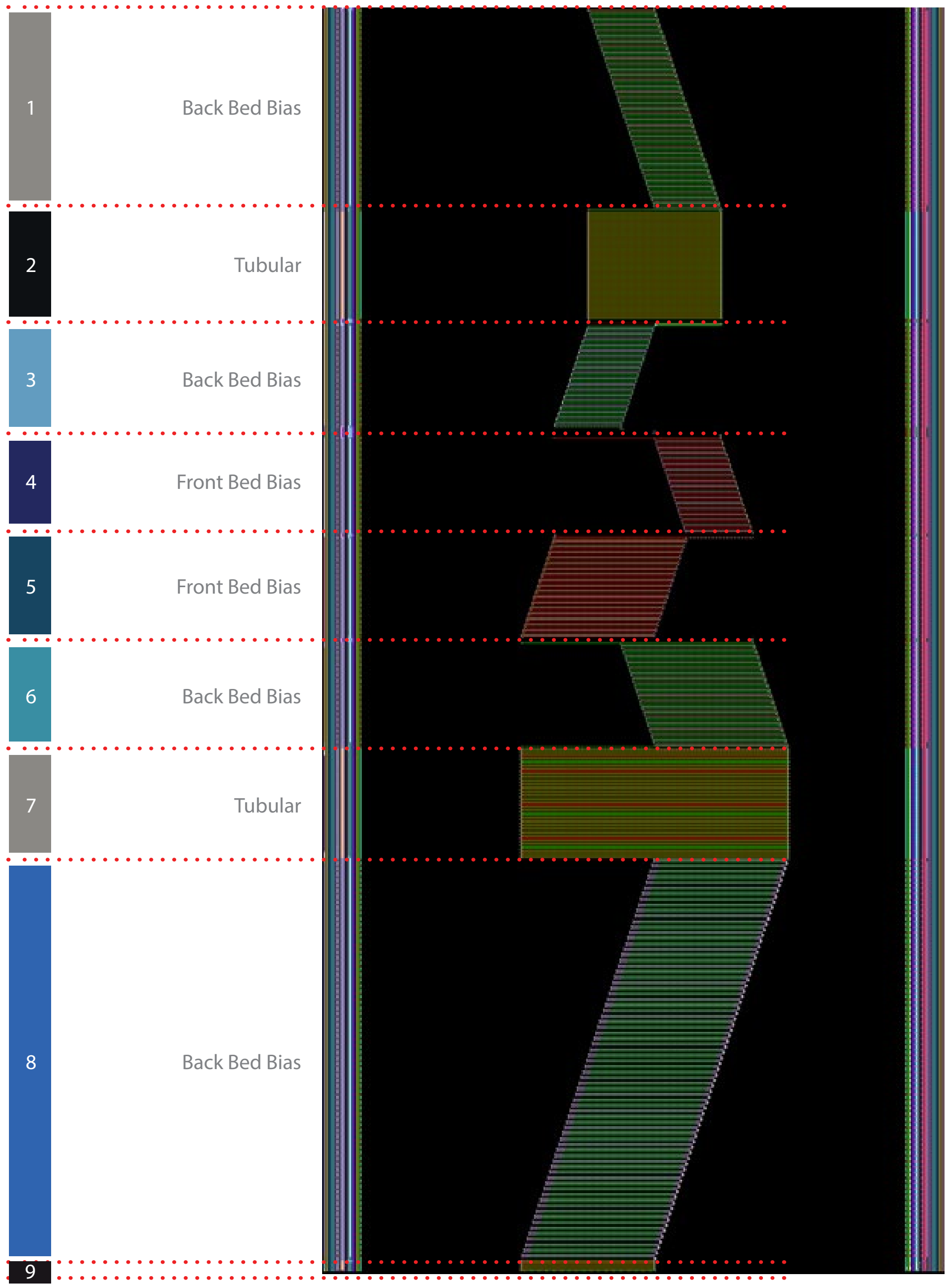
Form-building Journey of 3-Dimensional Cubic Geometric Forms



Notes to the Manual

Initiate	Fabrication is initiated with the selection of a knit operative in the format of a programmed component
Configure	The programmed component is oriented and scaled as required
Develop	The completed program is developed ready for fabrication
Extend	An additional operative (programmed component) is selected Geometries can be cycled through 'Extend' without limit to create compositions.
Compose	Operatives are combined through two construction techniques: Merge - merging of two or more operatives to create a single programmed component Integrate - sequential fabrication such that use of one operative follows the other
Fabricate	The developed program is uploaded to the knitting machine and a 3-dimensional textile form is fabricated
Operative	A category of geometric shaping distinguishable by both construction technique and resultant form
Attributes	Textual description and visual notations describing geometric shaping of an operative
Construction Technique	Textual descriptions of key construction techniques
Compressed Program	An instructive program in the format of Shima Seiki's programming language
Process Mapping	A mapping of front and back needle beds to 3-dimensional fabricated
Fabricated Form	Knitted 3-dimensional geometric form





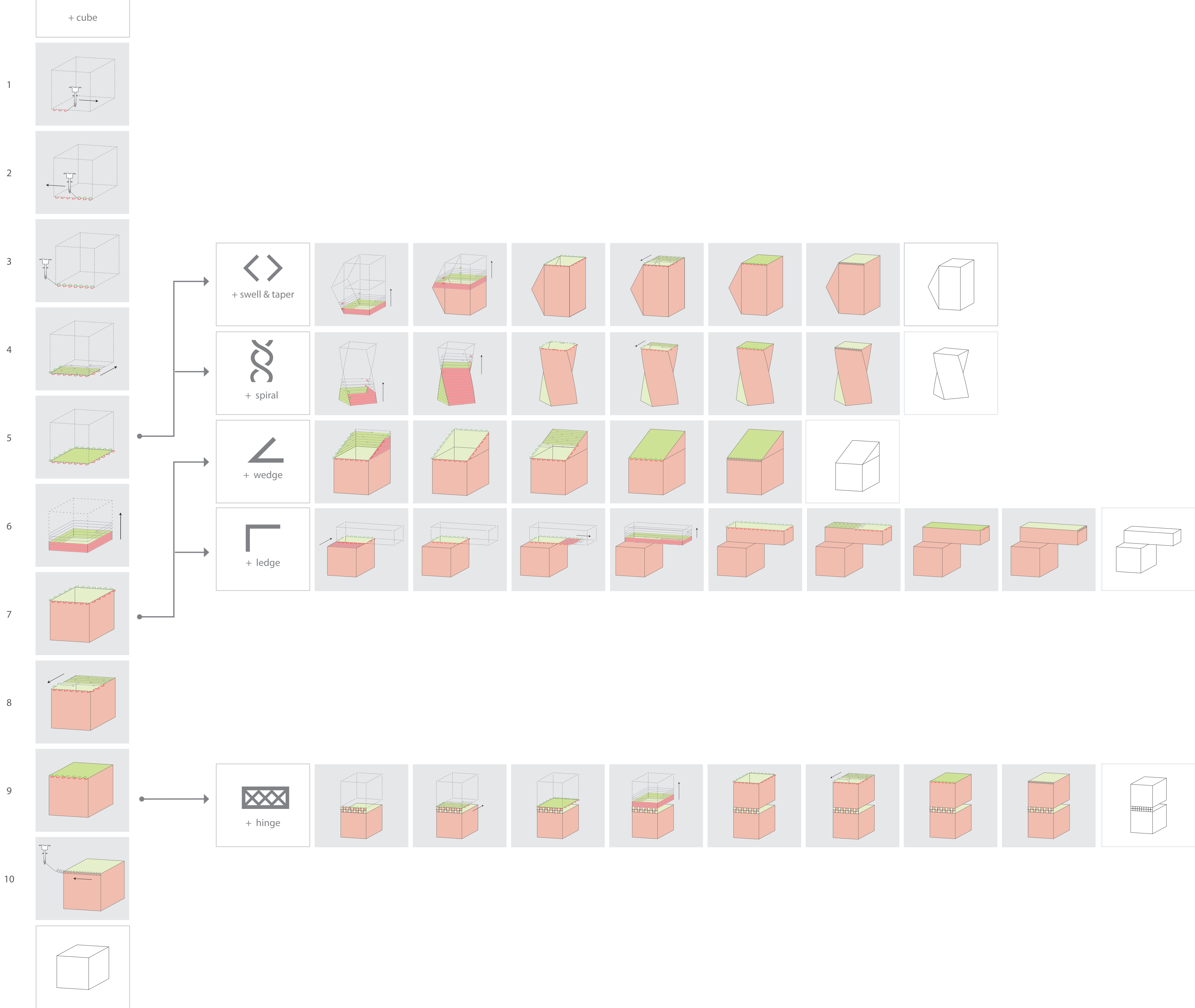
COMPRESSED PROGRAM

DEVELOPED PROGRAM

Process Mapping of 3-Dimensional Cubic Geometric Form

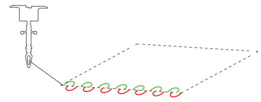
Appendix A

- knit on front bed
- knit on back bed
- surface constructed on front bed
- surface constructed on back bed
- loop held on front bed
- loop held on back bed
- loop knitted on front bed
- loop knitted on back bed
- outline of intended form
- outline of constructed form
- direction of carriage
- direction of surface construction
- binding off



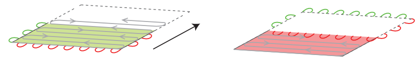
Construction Techniques, Cubic Geometric Form

Set-up Row



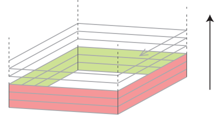
Construction is initiated with a closed tubular set-up.
The width of this row of knitting is equal to the starting width of the cubic form.
This set-up row could be adapted to an open tubular set-up to allow an opening into the form. Different set-up techniques offer different finishes with regards to elements such as visual aesthetic and stability.

Bias Knitting



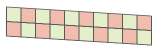
Construction occurs on a single bed in a diagonal direction. The diagonal direction allows for a plane to be constructed such that the right and left side edge loops on each row of knitting are held as the plane is fabricated.
The held loops form the edge of a cubic form, whereby tubular knitting following the bias fabrication is constructed in a perpendicular direction to the bias knit plane.
Bias knitting is used to construct the top and bottom planes of a cube, with the width of a bias knit plane being equal to the width of a single plane.

Tubular Knitting



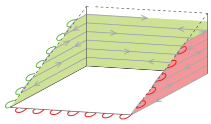
Circular construction spanning fabrication on front and back beds.
The first row of tubular construction picks up the held loops left by the bias knit plane. Stitch direction is perpendicular to the bias knit.
The width of front and back bed fabrication always even in length and in combination is equal to the width of four planes. However, not all planes are necessarily the same width. That is, the same tubular construction can be a square cube or a rectangular cuboid. The width and length of the bias knit plane before the tubular, and hence the lengths of the held loop edges inform the width of the tubular planes.

Interlock



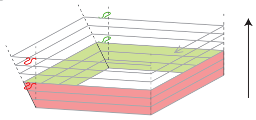
An independent component creating a join between two geometries.
In this research an interlock feature was used.
Variations could include stitch type, proportions and shape of the join.

C-knit



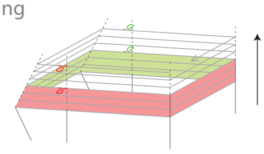
Short-row knitting allows for loops to be added in some areas of the knitted surface and held in others.
The proportions by which rows of knitting are shortened creates differing dimensions in the wedge that is created.

Inside Widening



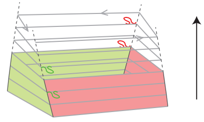
Inside widening within a tubular segment of knitting.
The construction technique introduces additional loops within a plane or surface rather than at is edges.
Additional loops are added within a course of knitting.
In this geometry the same number of loops are added to both front and back beds, though the positioning of the loops may vary.

Inside Narrowing



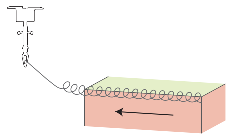
Inside narrowing within a tubular segment of knitting.
The construction technique reduces loops within a plane or surface rather than at is edges.
In this geometry the same number of loops are reduced on both front and back beds, though the positioning of the loops may vary.

Rotation



A combination of racking and transfer of stitches across needle beds creates a rotational or twisting motion within the tubular segment of a geometry.

Bind-off

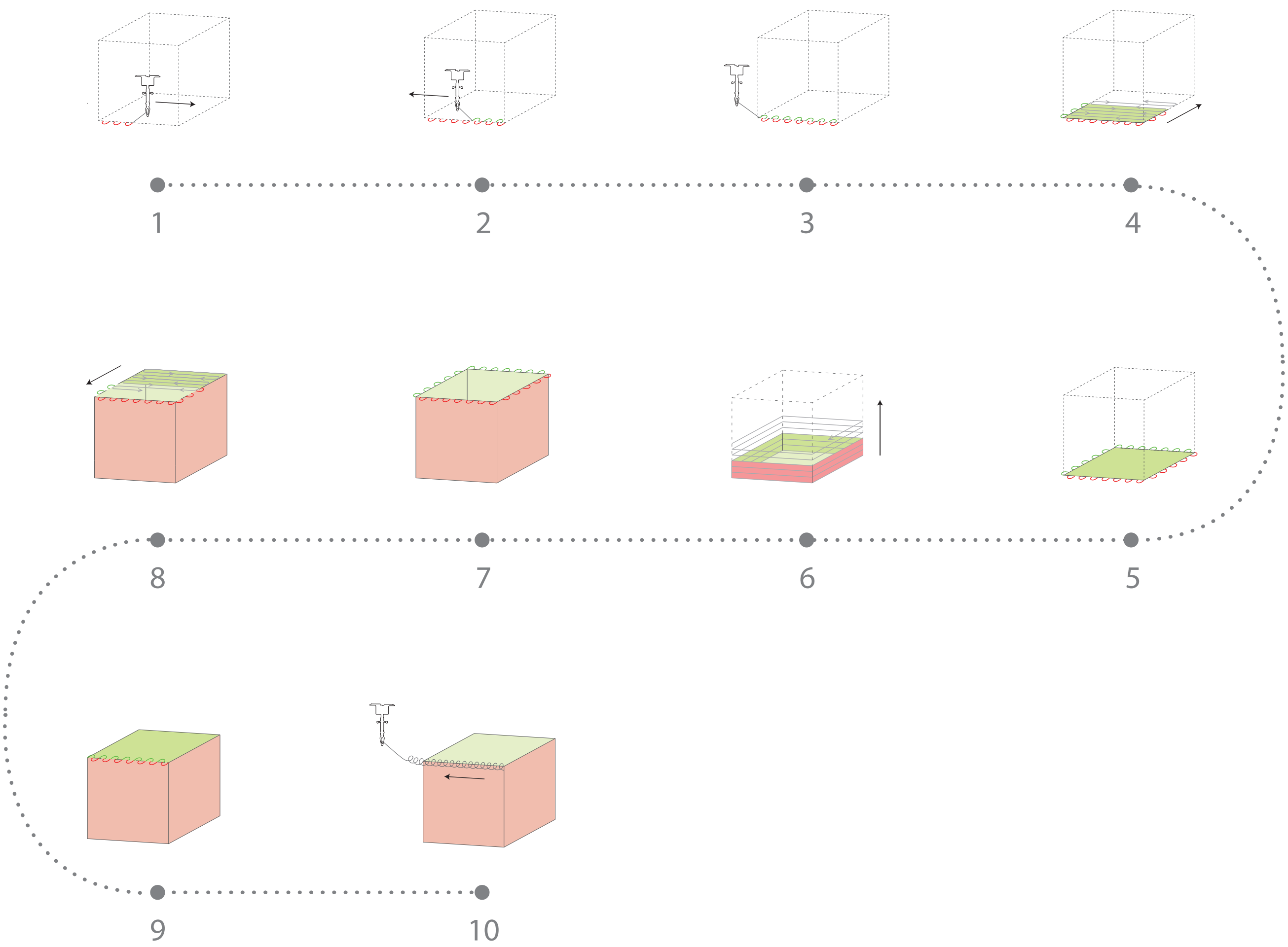


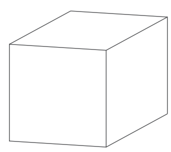
viii

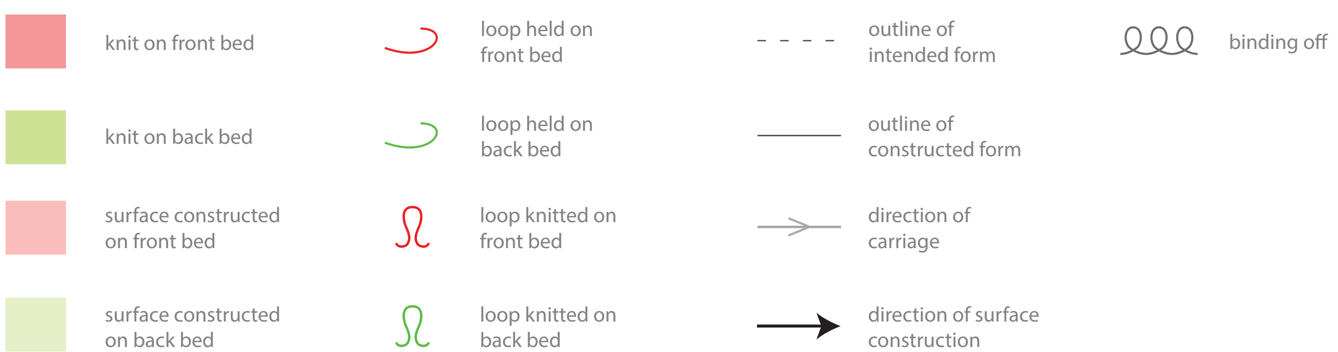
The last front and back bed rows are locked such that they cannot unravel.
A bind off can be used to close a form by joining the front and back bed edges, or the edges can be locked separately so that the form remains open. A combination of the two is also possible.
Different bind-off techniques offer different finishes with regards to elements such as visual aesthetic and stability.

cube

Process Mapping







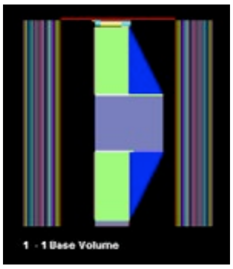
Operative

+ cube

Attributes

- a geometry of six planes, with each perpendicular to its adjacent planes

Compressed Program

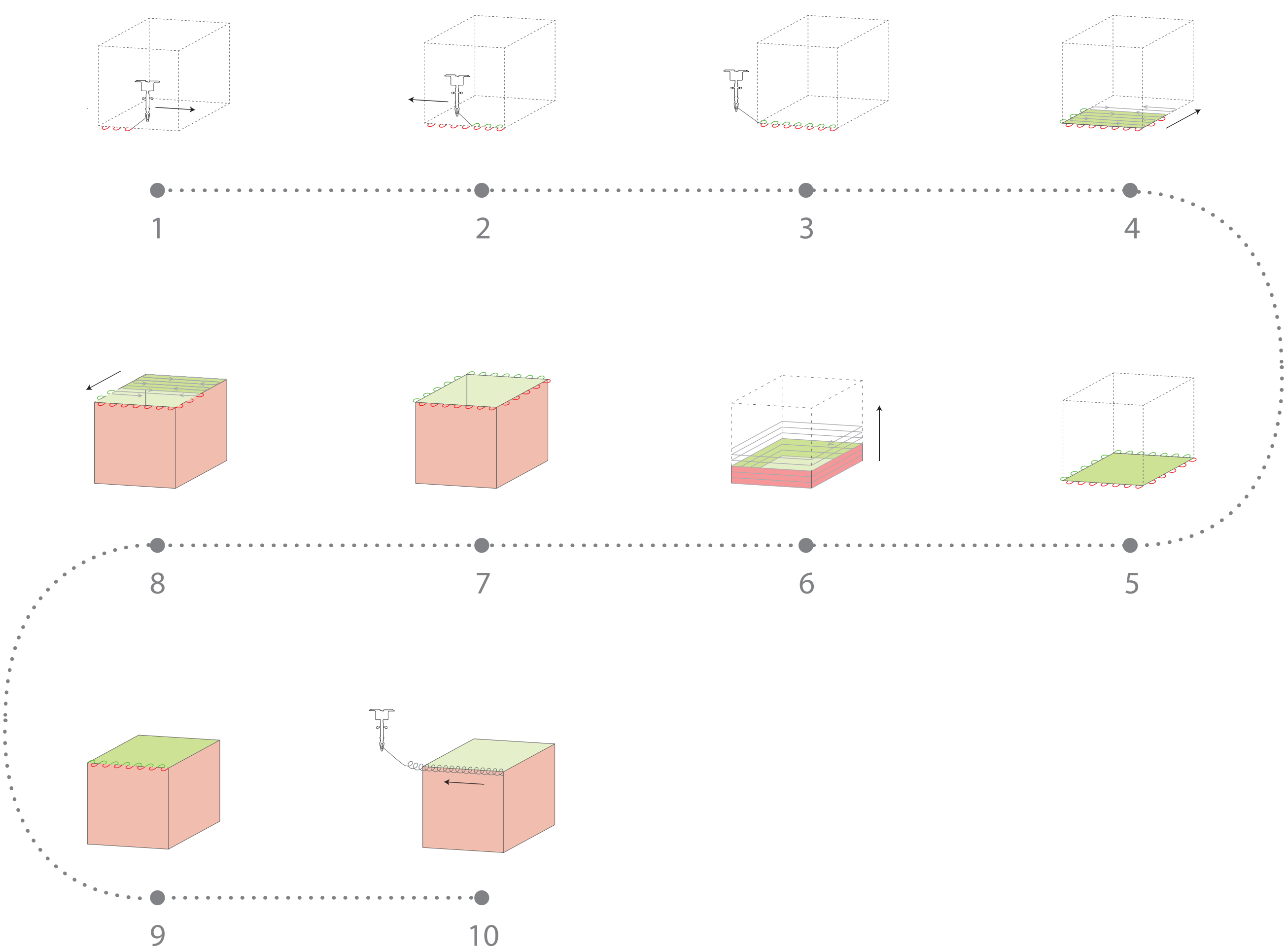


Construction Notes

- bias knit
- on front or back bed to create planes from different edges
- can be constructed with bias from left to right or vice versa

Fabricated Form

Process Mapping



knit on front bed

knit on back bed

surface constructed on front bed

surface constructed on back bed

loop held on front bed

loop held on back bed

loop knitted on front bed

loop knitted on back bed

outline of intended form

outline of constructed form

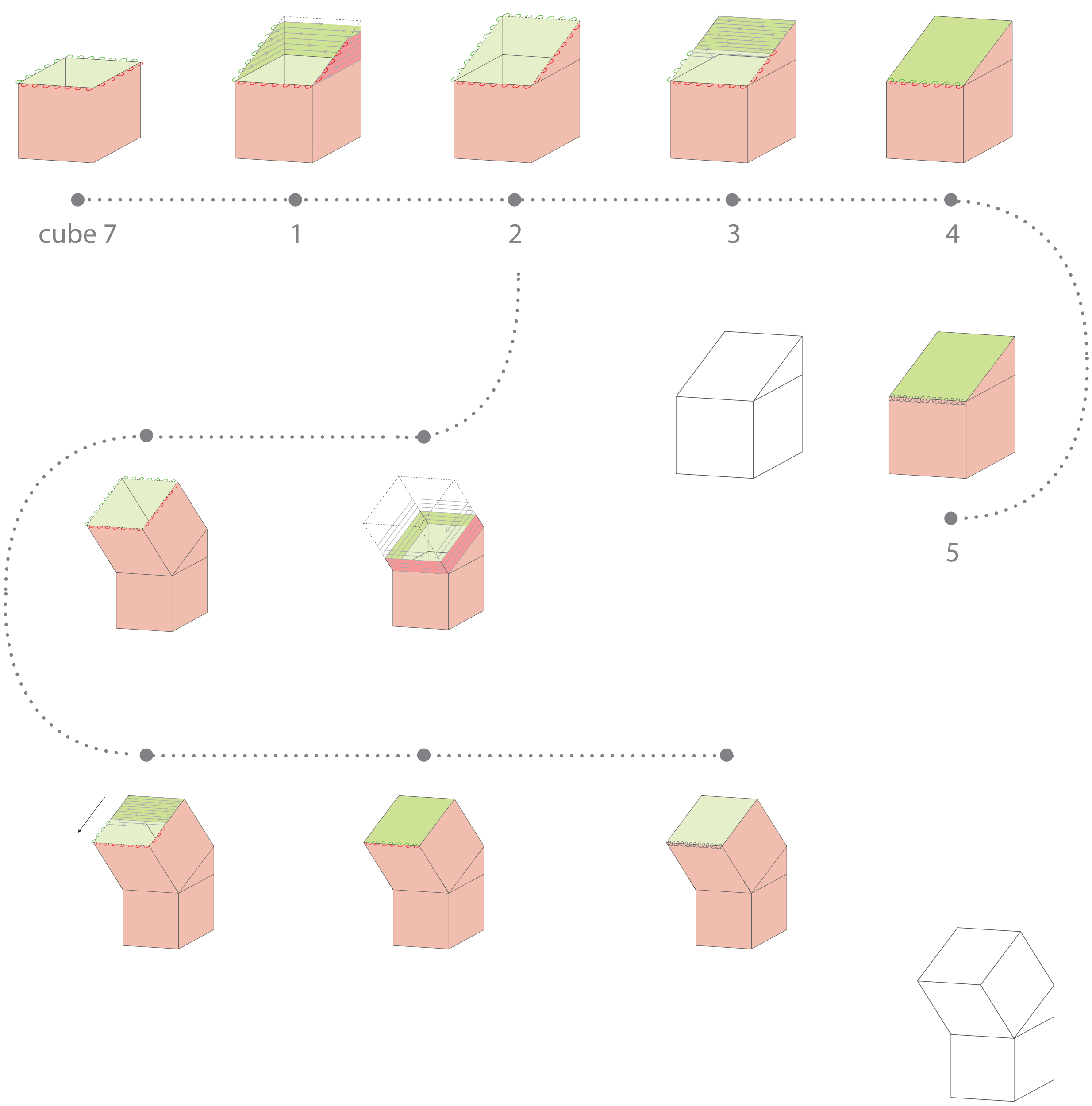
direction of carriage

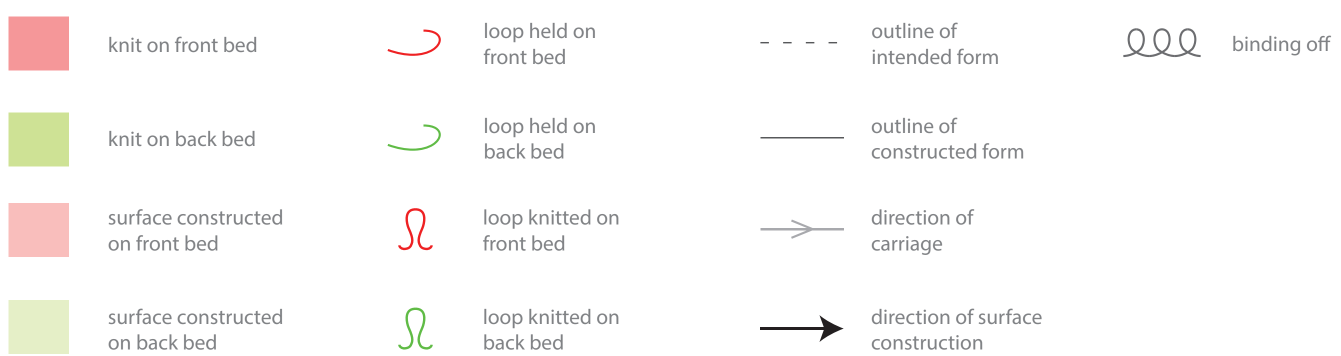
direction of surface construction

binding off

+ wedge

Process Mapping





Operative

+ wedge

Attributes

- triangular prism which can be integrated within the tubular knit or bias knit planes of cuboid fabrication

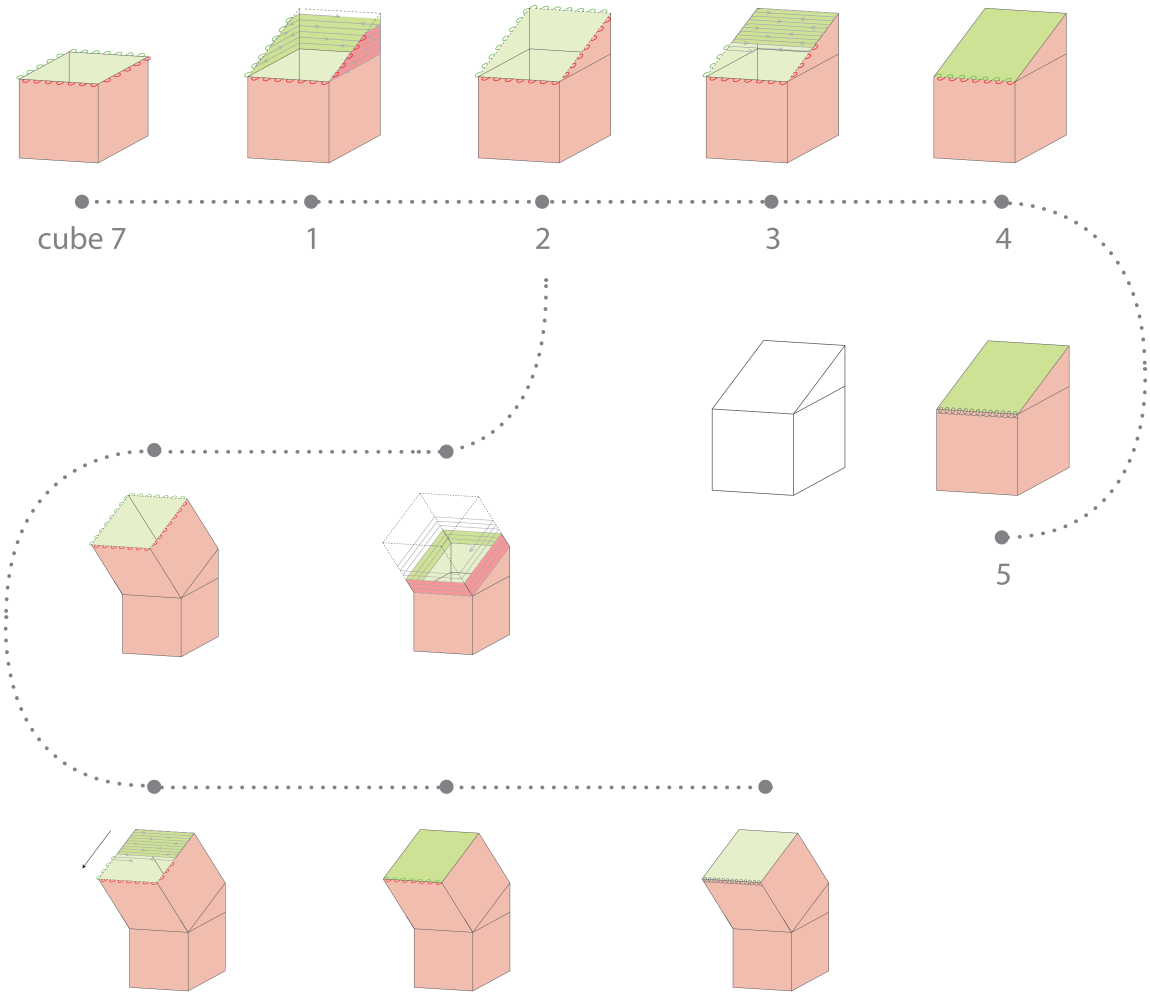
Compressed Program

Construction Notes

- flechage or short-row in tubular knitting
- knitted loops are added through additional courses of knitting
- can expand through bias knitting

Fabricated Form

Process Mapping



knit on front bed

knit on back bed

surface constructed on front bed

surface constructed on back bed

loop held on front bed

loop held on back bed

loop knitted on front bed

loop knitted on back bed

outline of intended form

outline of constructed form

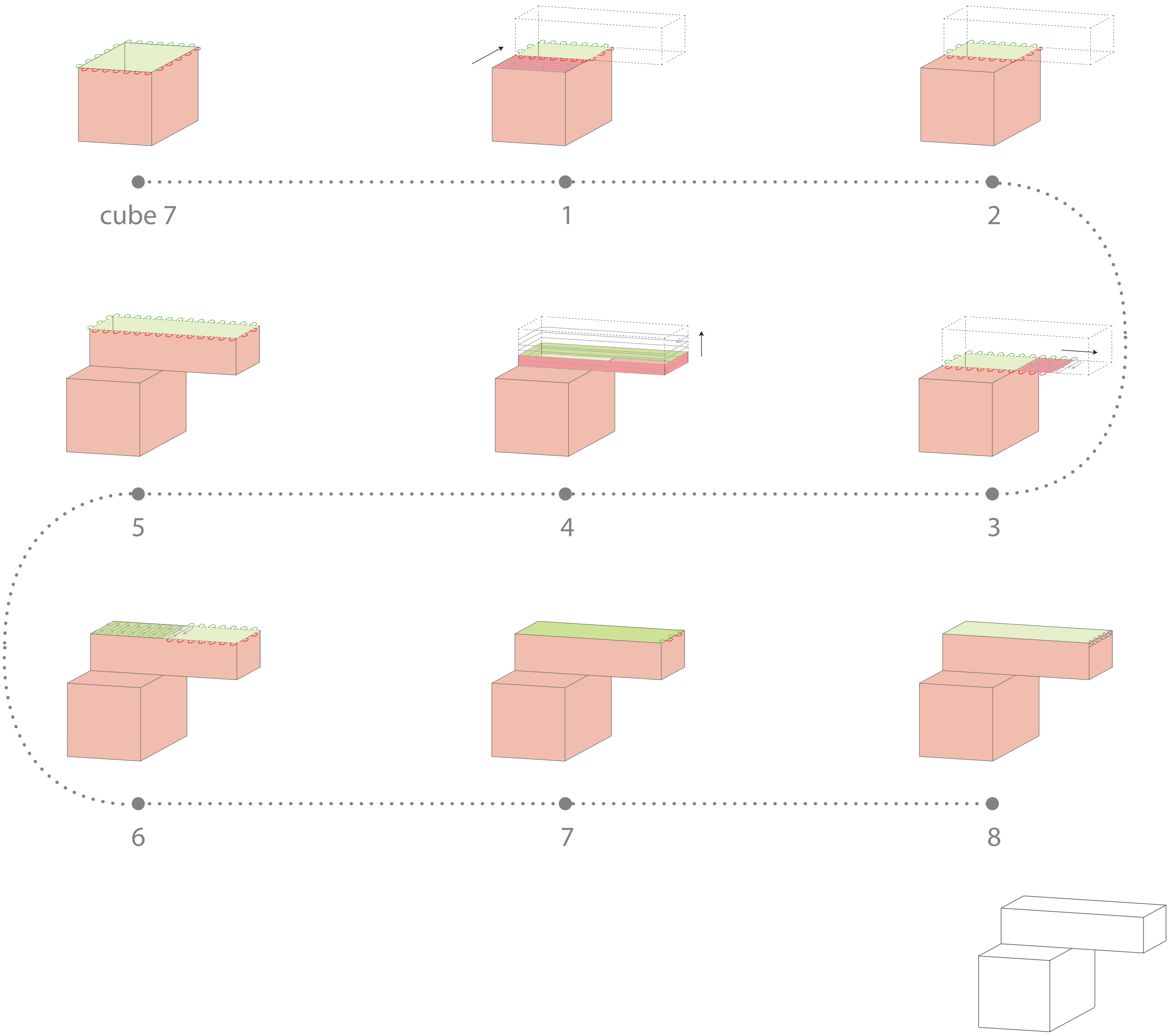
direction of carriage

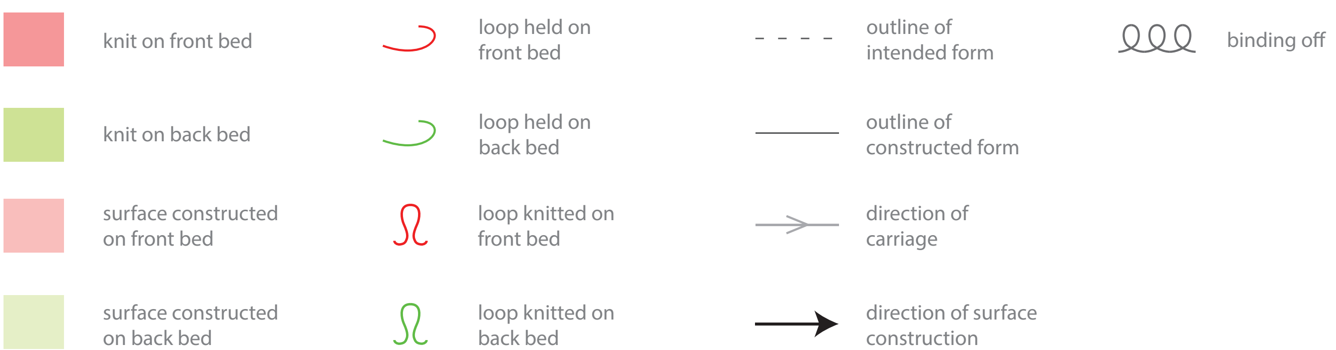
direction of surface construction

binding off

+ ledge

Process Mapping





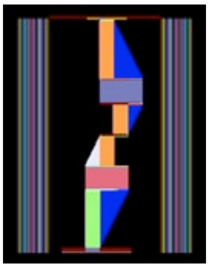
Operative

+ ledge

Attributes

- a perpendicular plane
- can be used to extend or shorten cubic geometries

Compressed Program

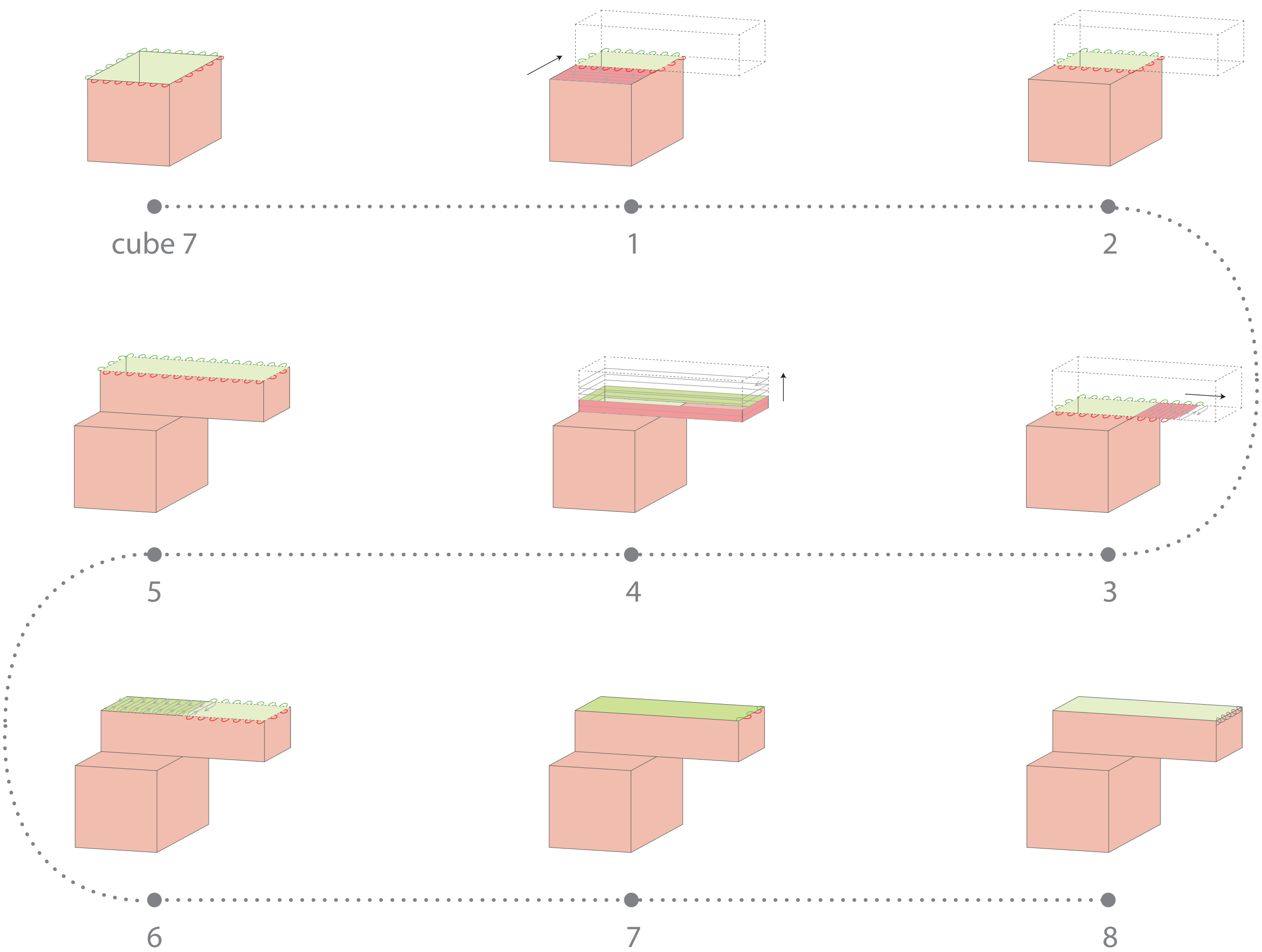


Construction Notes

- bias knit
- on front or back bed
- can be constructed with bias from left to right or vice versa

Fabricated Form

Process Mapping



knit on front bed

knit on back bed

surface constructed on front bed

surface constructed on back bed

loop held on front bed

loop held on back bed

loop knitted on front bed

loop knitted on back bed

outline of intended form

outline of constructed form

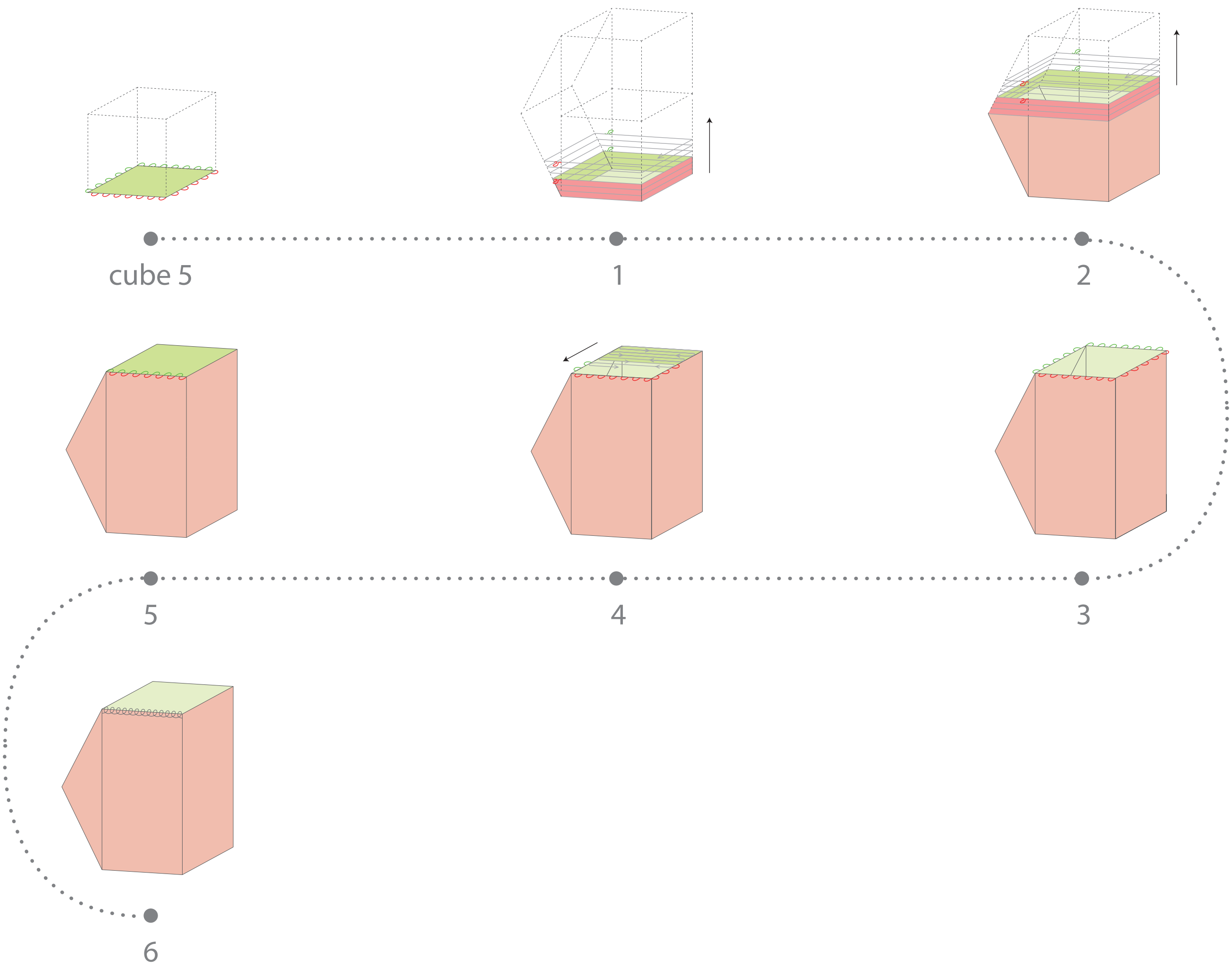
direction of carriage

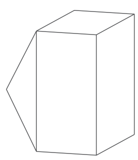
direction of surface construction

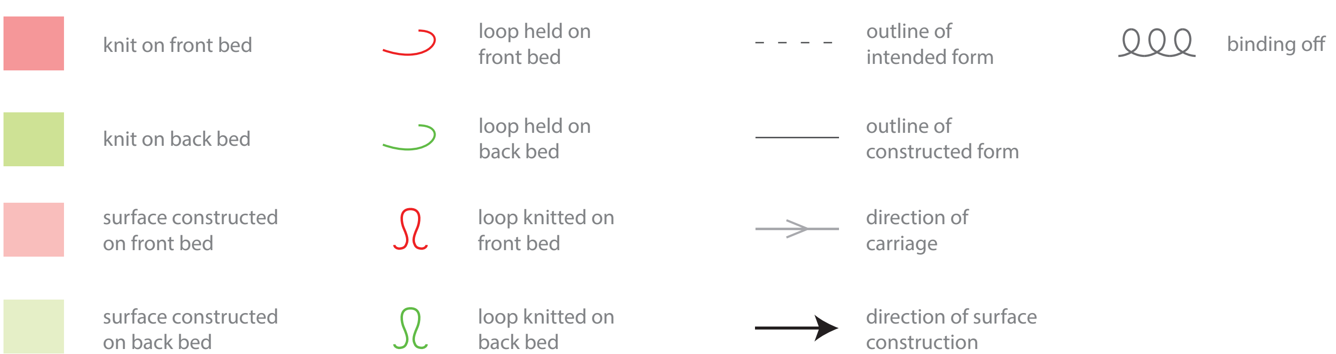
binding off

+ swell & taper

Process Mapping







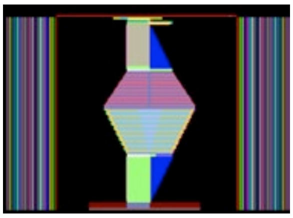
Operative

+ swell & taper

Attributes

- a triangular prism which can be integrated within the surfaces of tubular knit rather than at its edge
- primarily utilises inside widening and narrowing to ncrease or reduce the width of a plane

Compressed Program

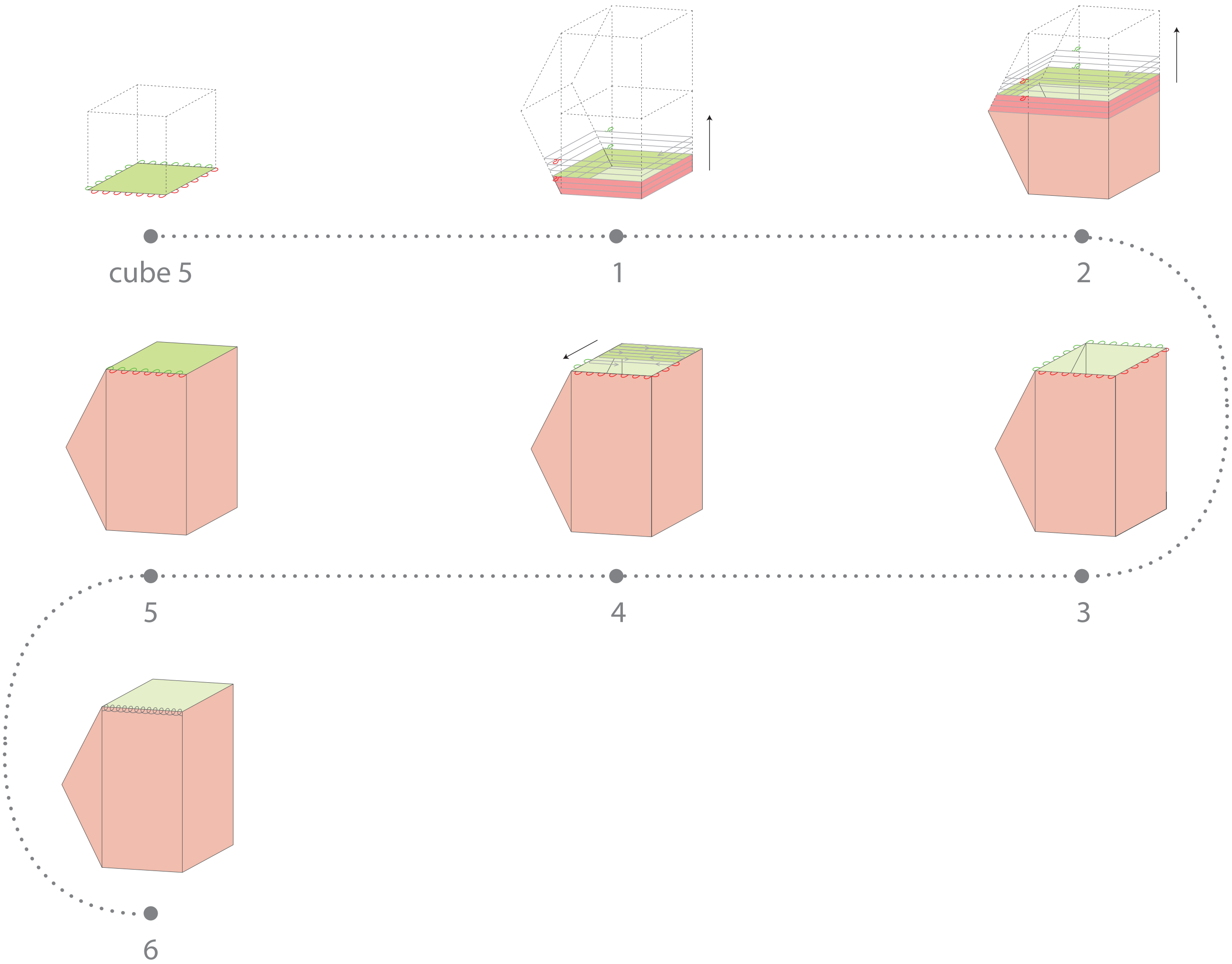


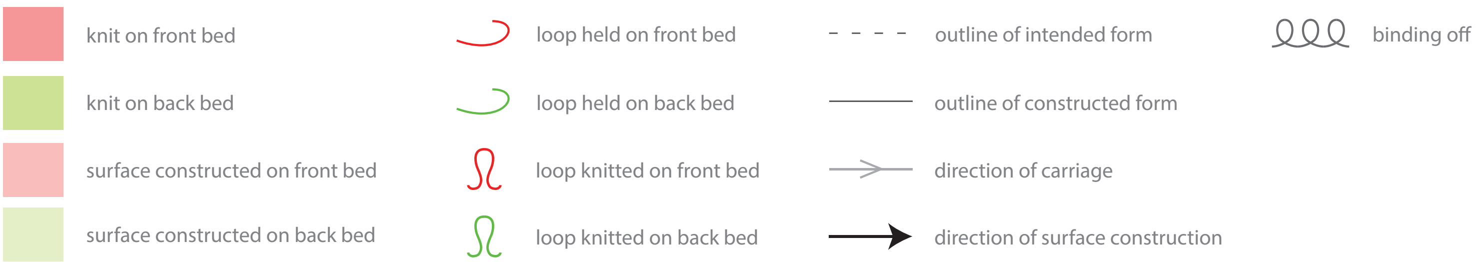
Construction Notes

- widening or narrowing through tubular knit component
- can be within a knitted surface or at its edges (inside or outside)
- knitted loops are added or removed within a course of knitting
- flechage

Fabricated Form

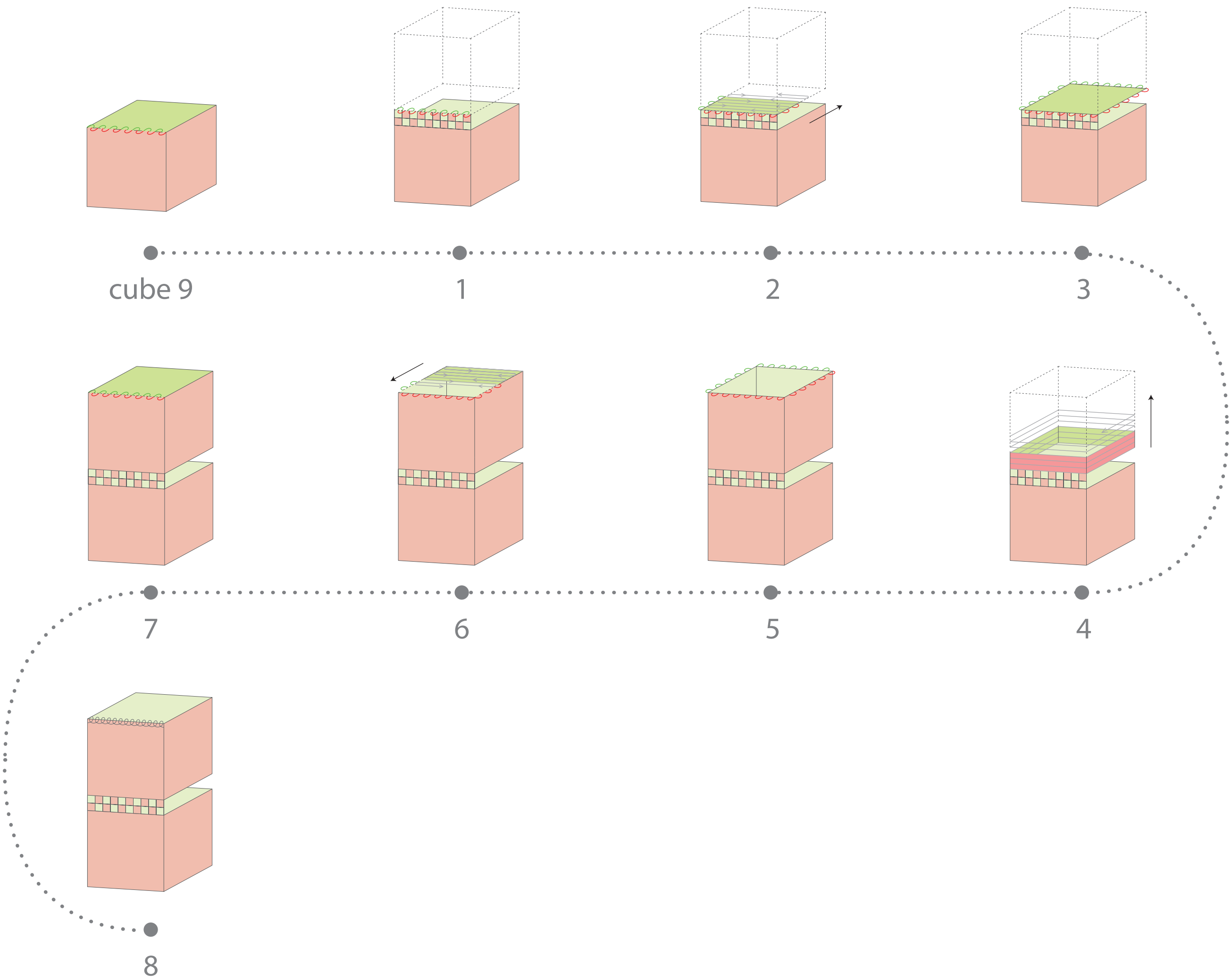
Process Mapping

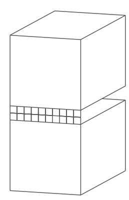




+ hinge

Process Mapping



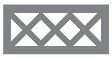
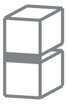


- knit on front bed
- knit on back bed
- surface constructed on front bed
- surface constructed on back bed
- loop held on front bed
- loop held on back bed
- loop knitted on front bed
- loop knitted on back bed
- outline of intended form
- outline of constructed form
- direction of carriage
- direction of surface construction
- binding off

Operative

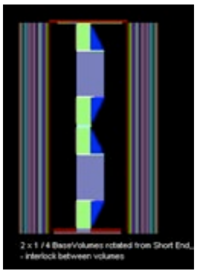
+ hinge

Attributes

- an independent component creating a join between two geometries

Compressed Program

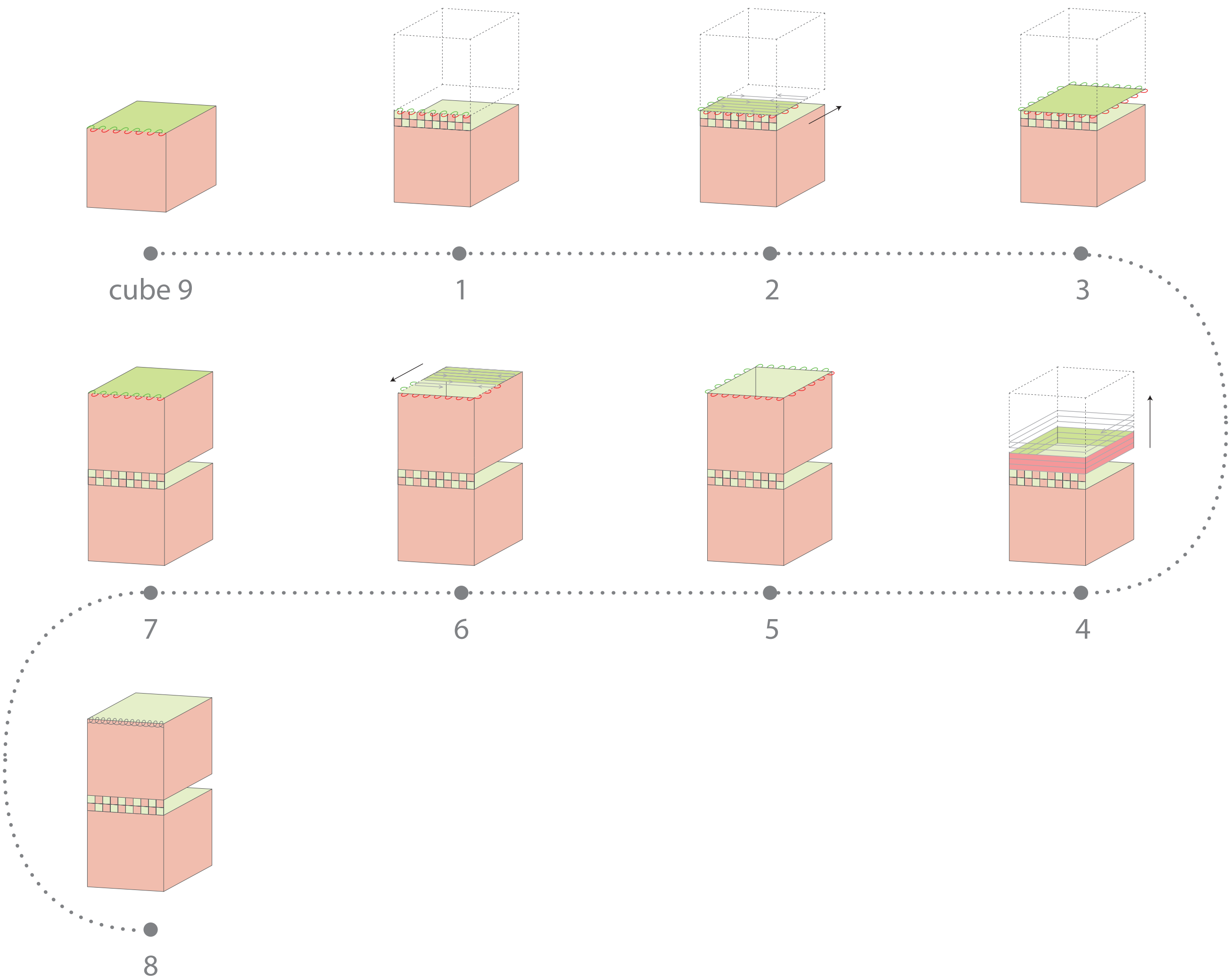


Construction Notes

- interlock

Fabricated Form

Process Mapping



knit on front bed

knit on back bed

surface constructed on front bed

surface constructed on back bed

loop held on front bed

loop held on back bed

loop knitted on front bed

loop knitted on back bed

outline of intended form

outline of constructed form

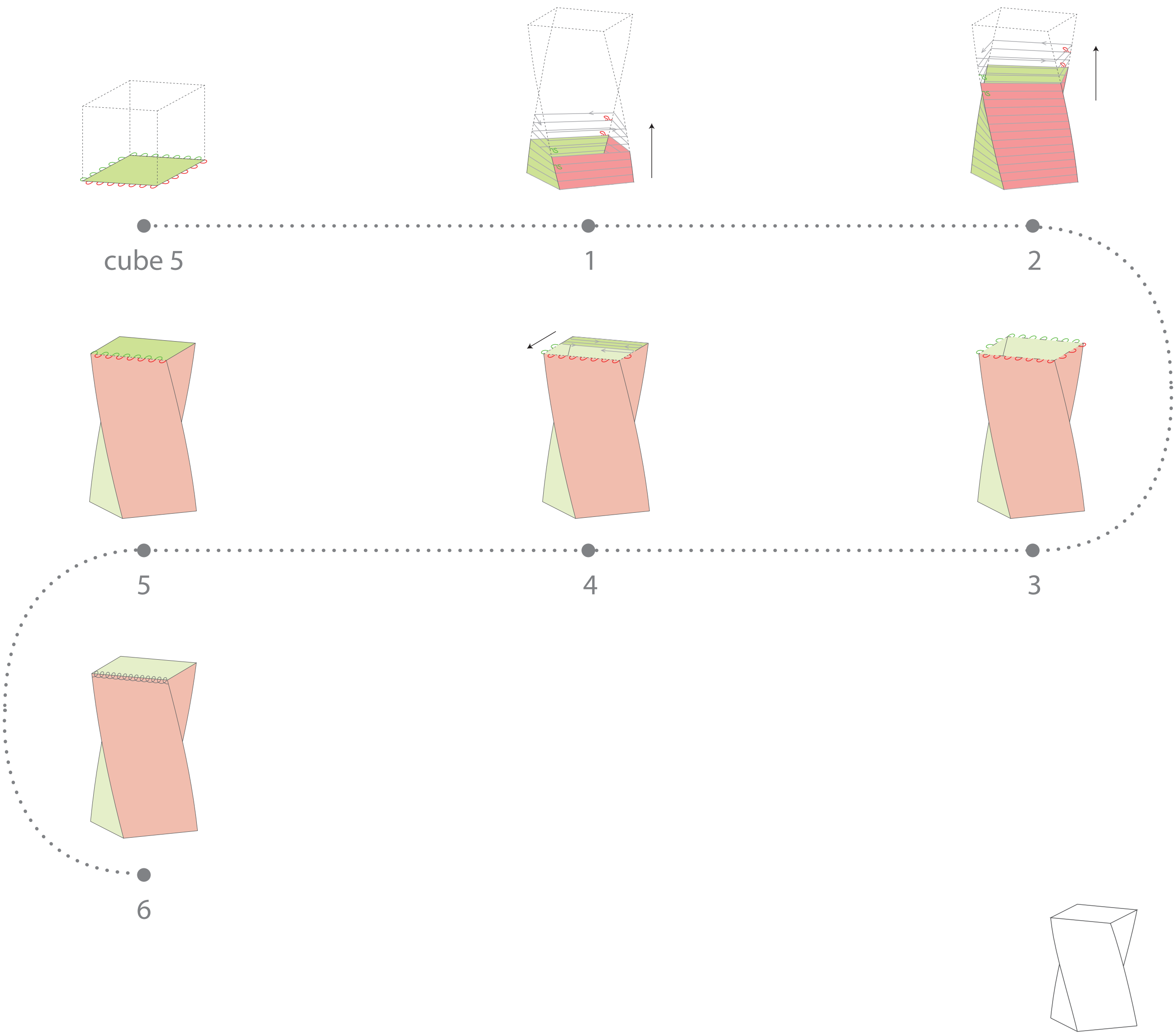
direction of carriage

direction of surface construction

binding off

+ spiral

Process Mapping



knit on front bed

knit on back bed

surface constructed on front bed

surface constructed on back bed

loop held on front bed

loop held on back bed

loop knitted on front bed

loop knitted on back bed

outline of intended form

outline of constructed form

direction of carriage

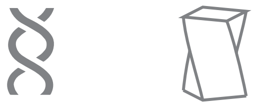
direction of surface construction

binding off

Operative

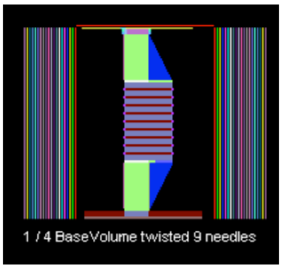
+ spiral

Attributes



- a rotational or twisting motion within a geometry

Compressed Program

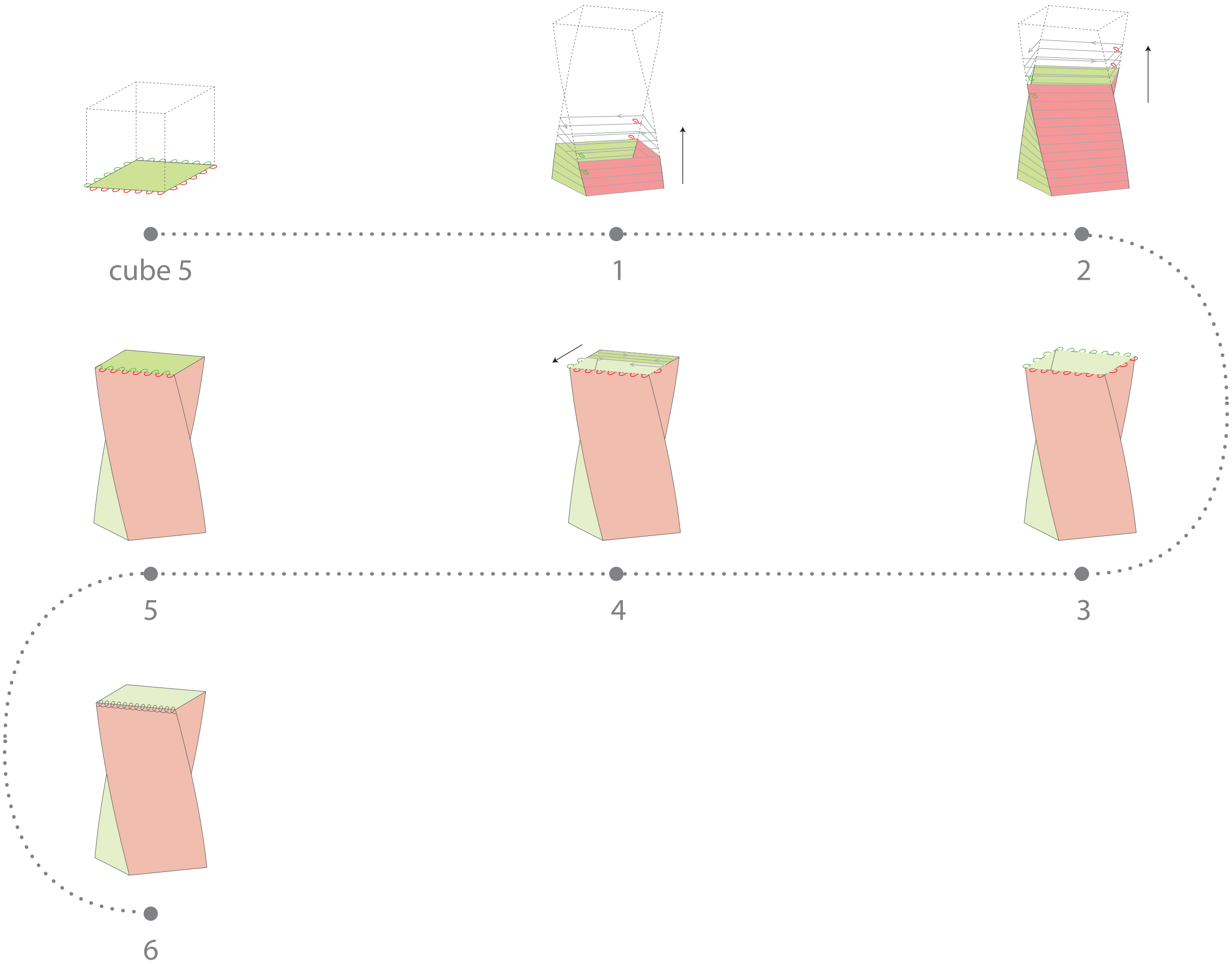


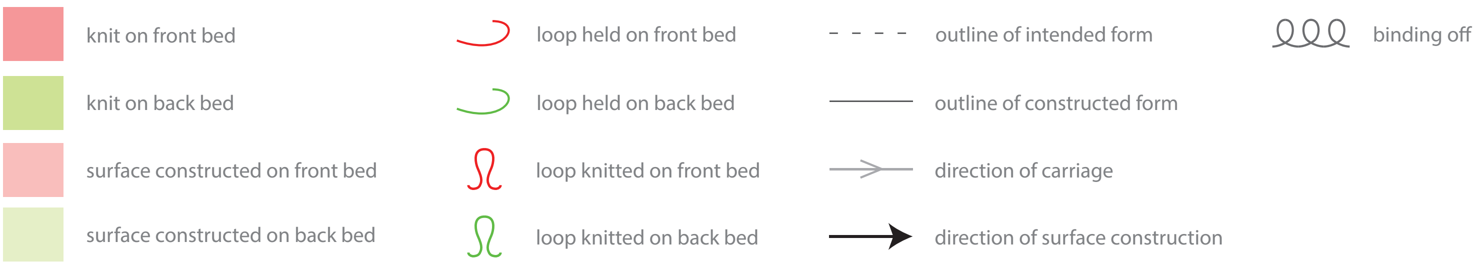
Construction Notes

- racking
- cross-bed stitch movement

Fabricated Form

Process Mapping

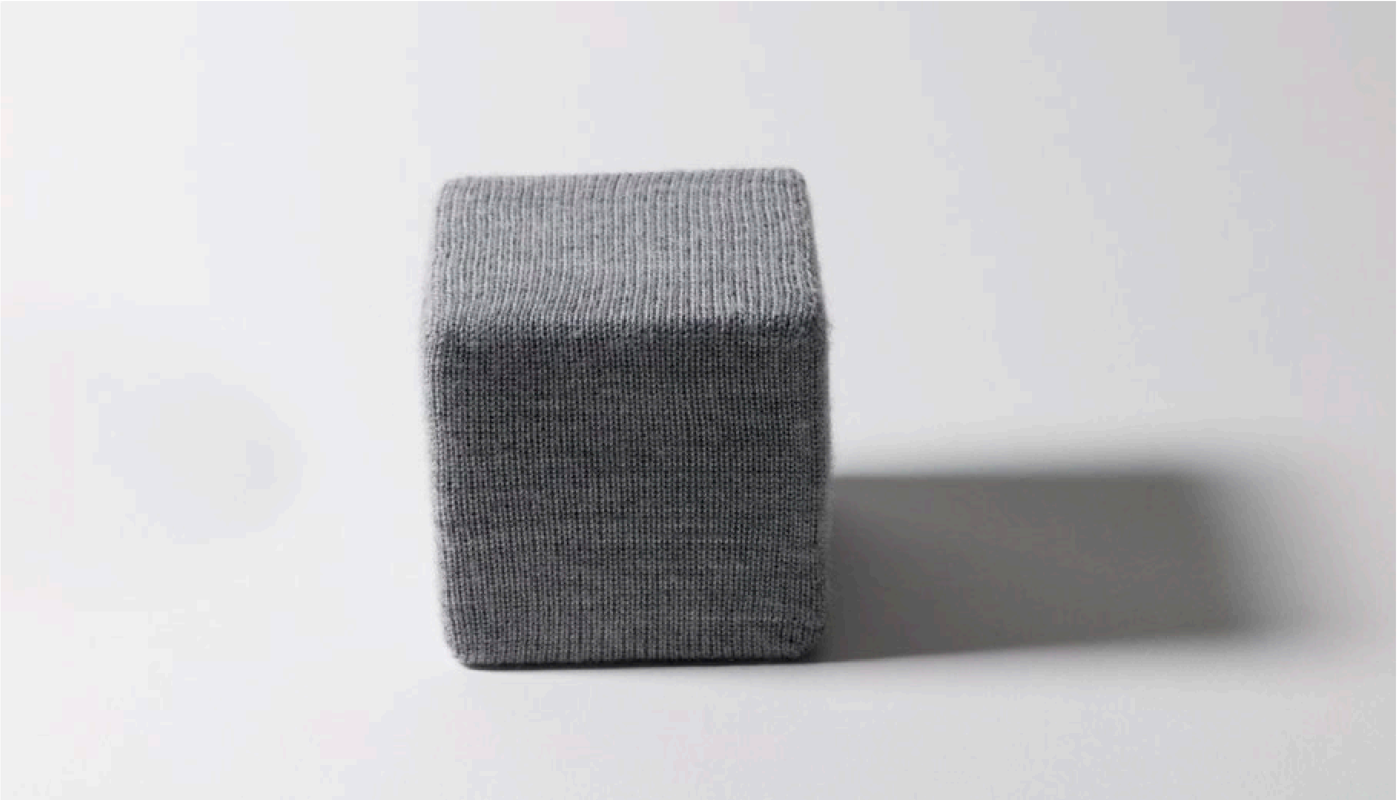




Compositions

Attributes		Construction Notes	Fabricated Form
- geometries composed of more than two operatives through an extend process	See Appendix A, Development Journey of 3-Dimensional Knit Geometries for detail of the extend process	 - Merge: merging of two or more operatives to create a single programmed component - Integrate: sequential fabrication in which use of one operative follows the other	

Appendix B
Catalogue of 3-Dimensional Cubic Geometric Forms



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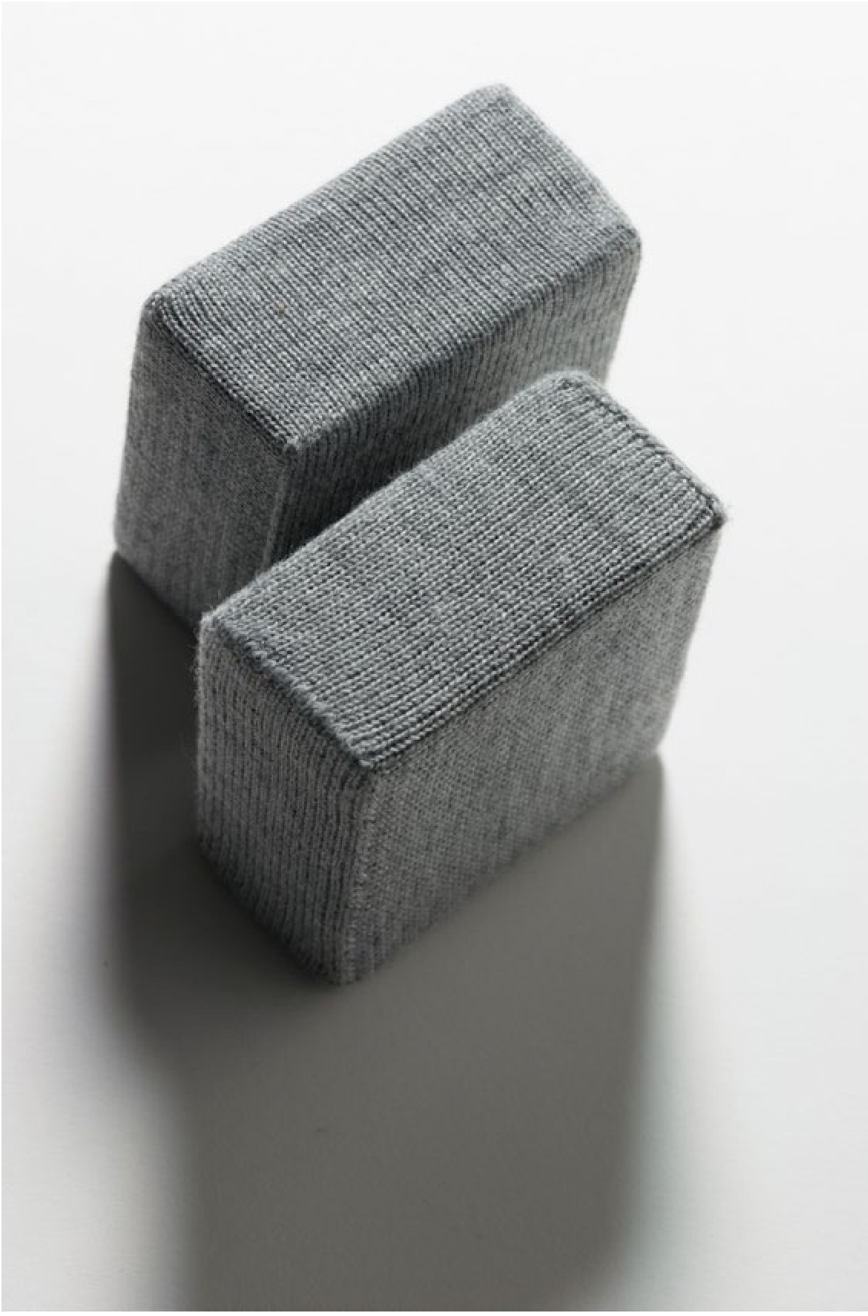
cube

cube



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cube

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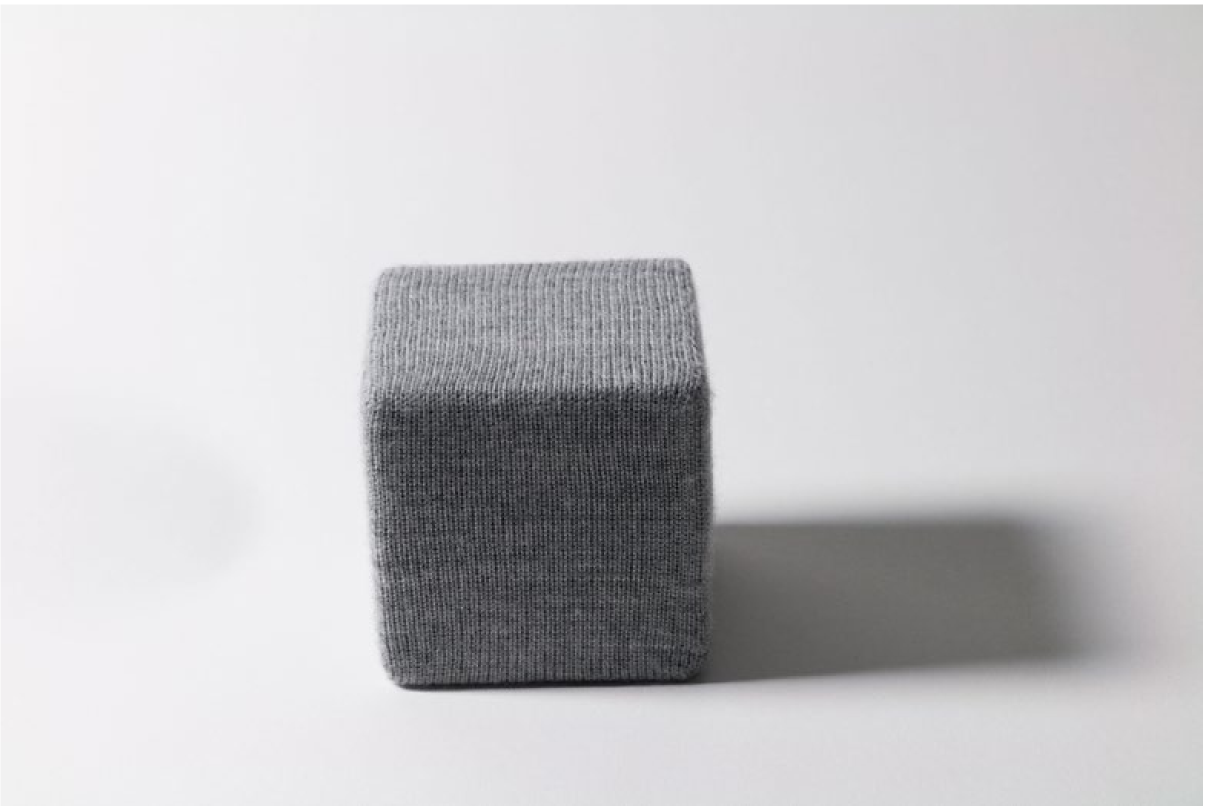
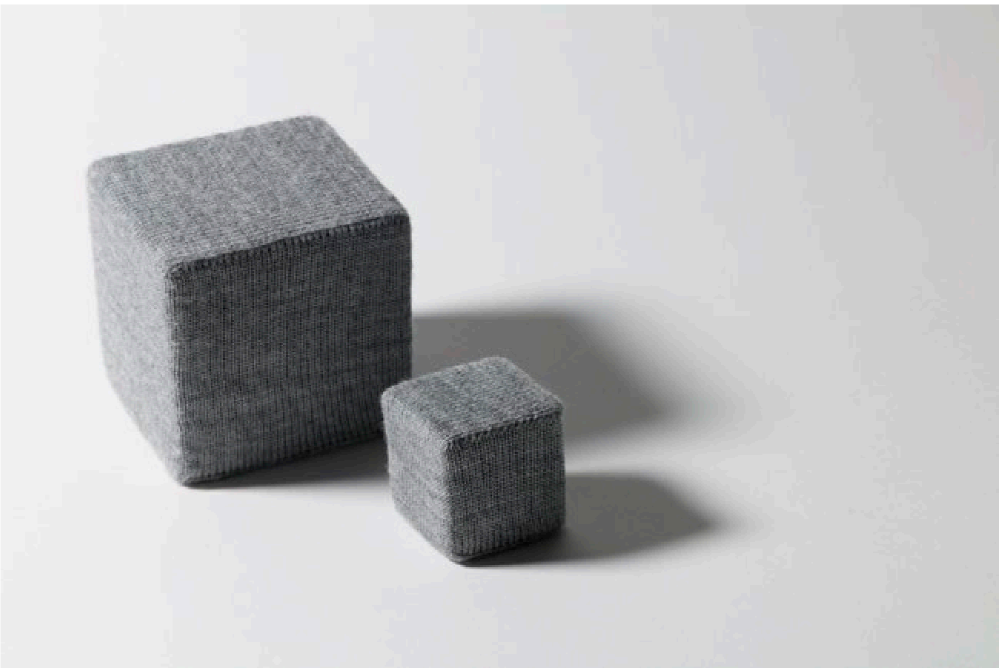
cube





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cube

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cube

+ wedge

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+ wedge

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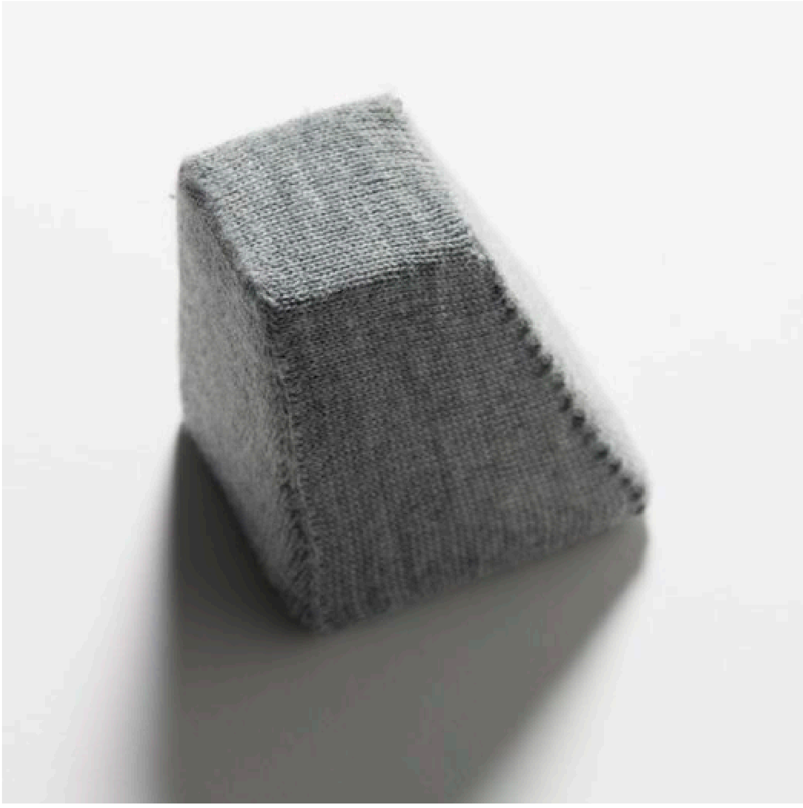
+ wedge



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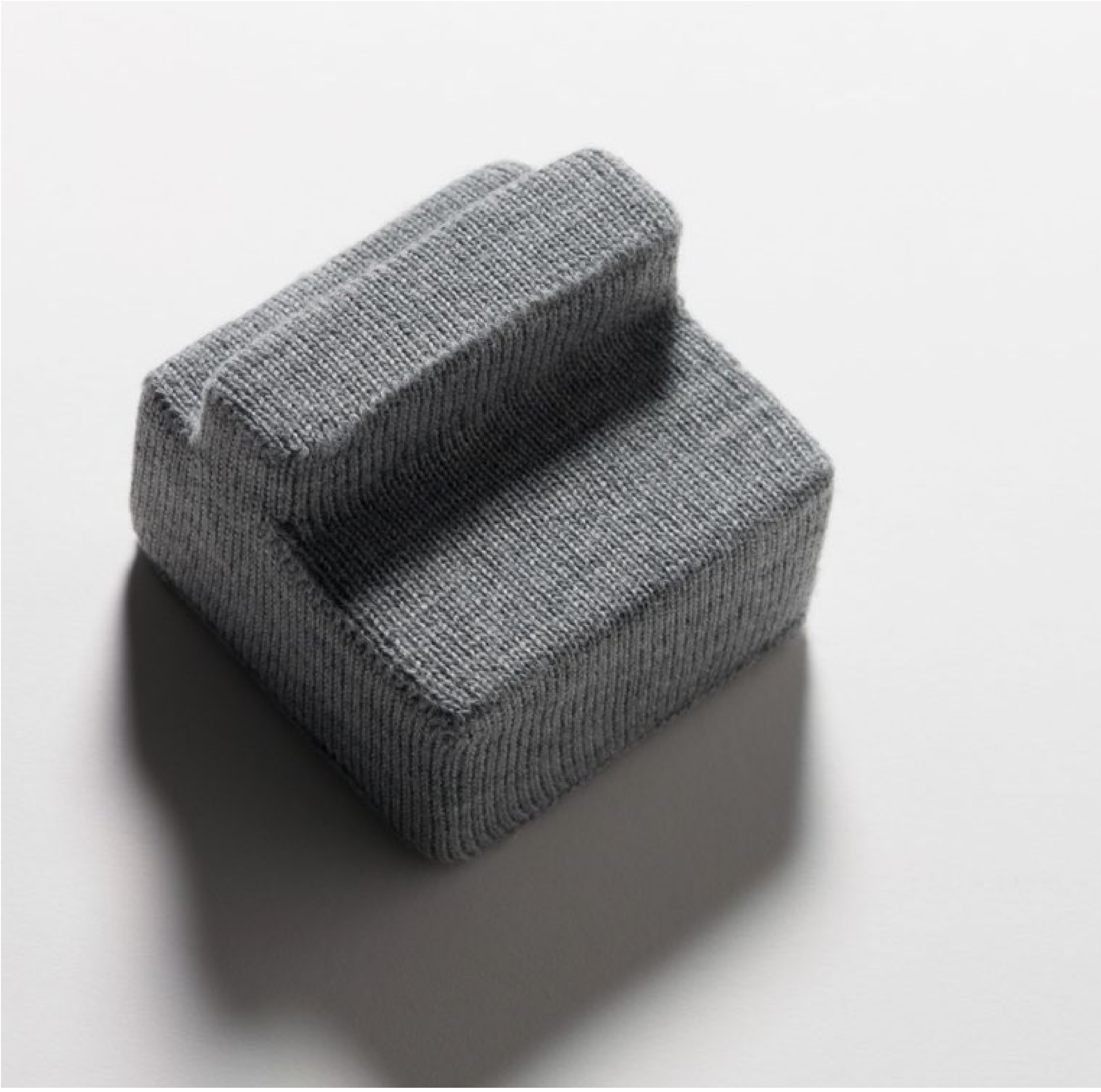
+ wedge

+ ledge

+ ledge

+ ledge

+ ledge



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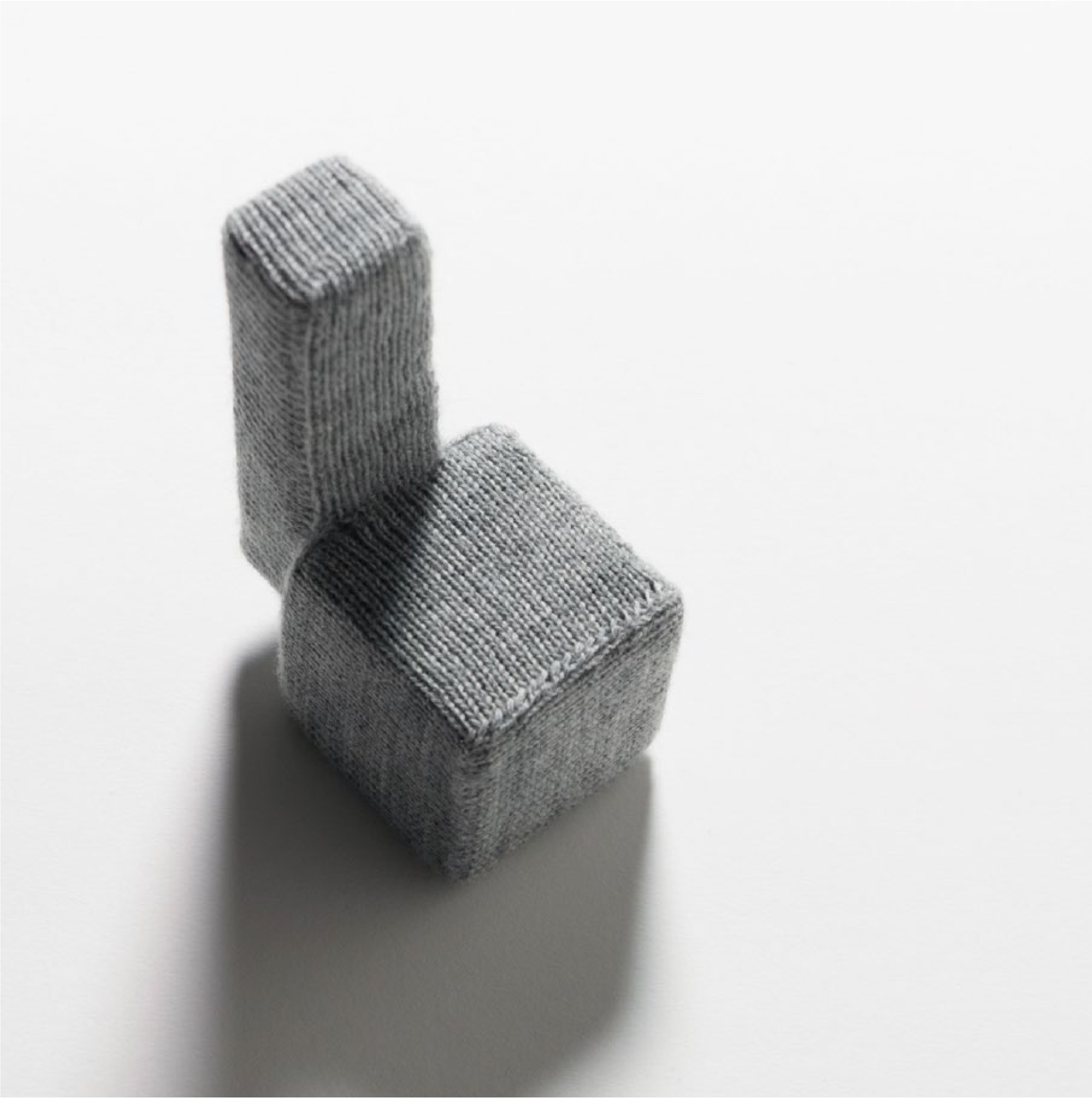

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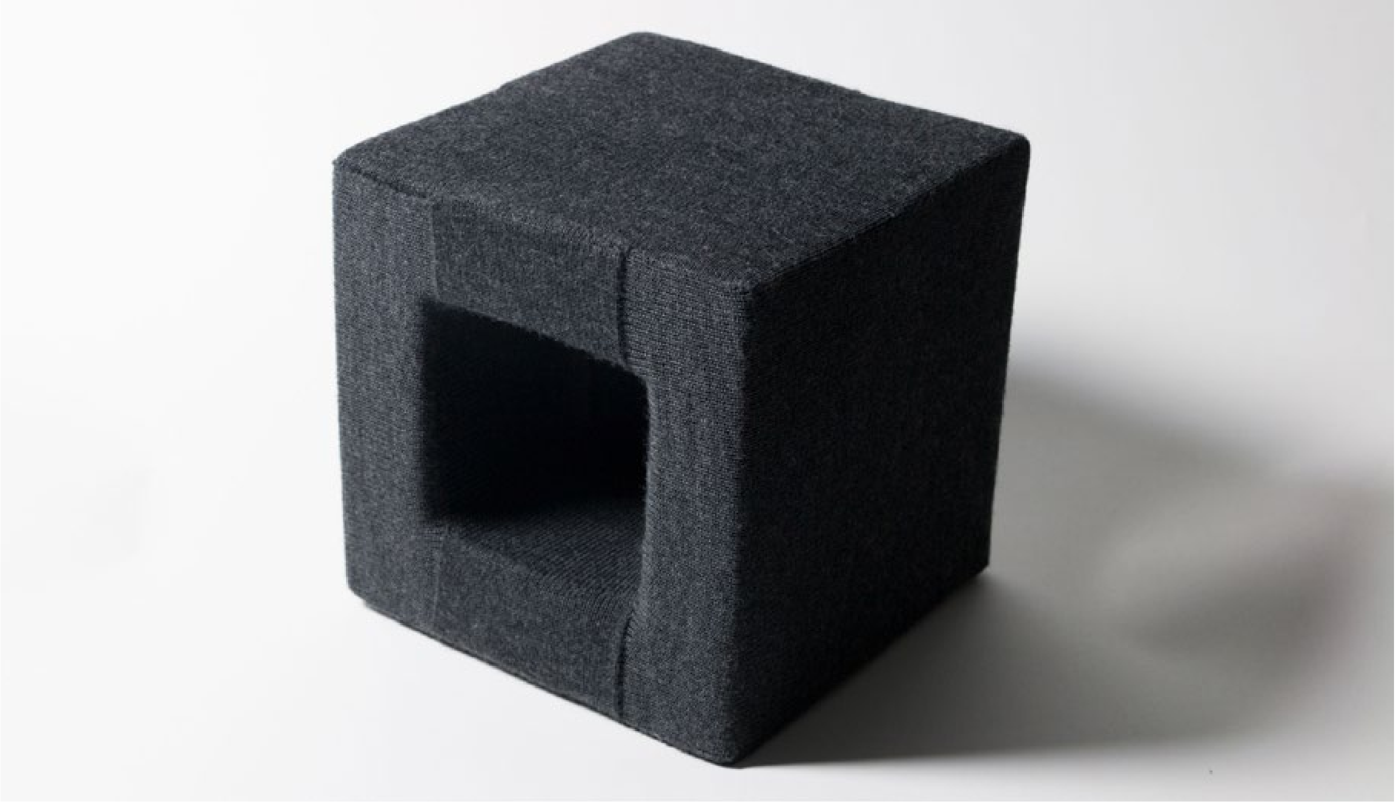
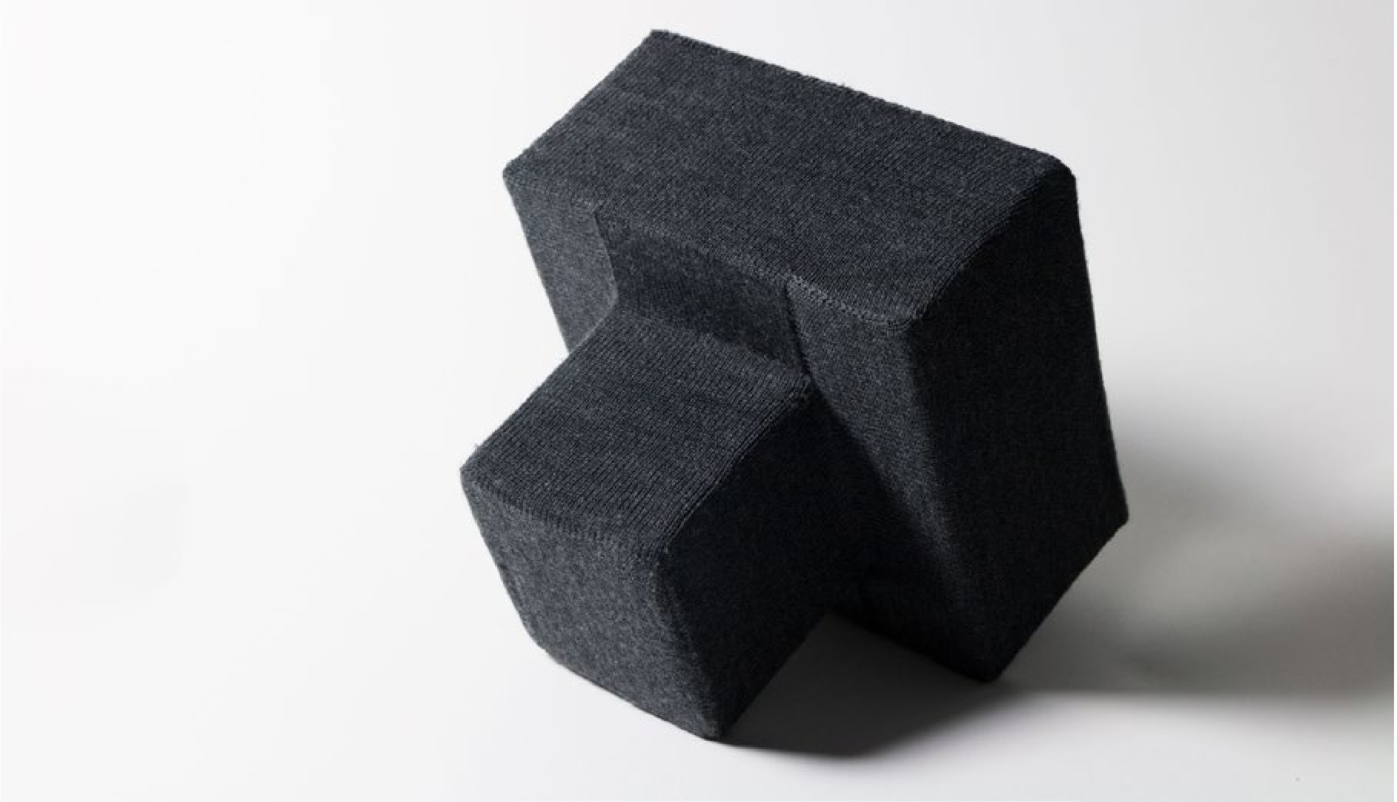
+ ledge



+ ledge



+ ledge

< >

+ swell & taper

+ swell & taper

<>

+ swell & taper

+ swell & taper

+ swell & taper

‹ ›

+ swell & taper

+ swell & taper

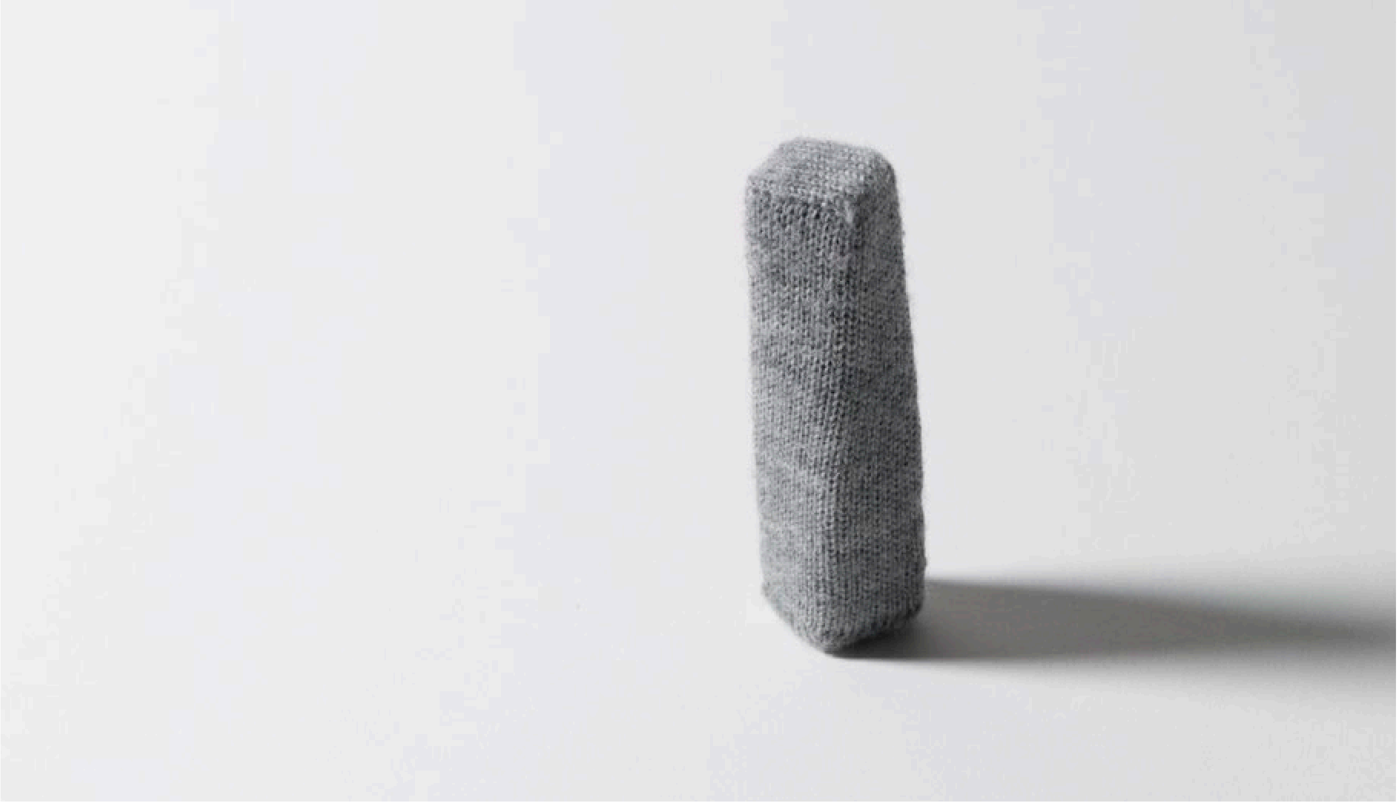
+ hinge

+ hinge

+ hinge

+ hinge

+ spiral



+ spiral

compositions

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