INDEPENDENT INNOVATION THROUGH DIGITAL FABRICATION FOCUSING ON EXPLORATIONS IN RECONFIGURABLE PIN TOOLING

By

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Abstract and Keywords

This research investigates how new manufacturing concepts can be developed by individual practitioners and small manufacturing companies facilitated by an increased diffusion of digital fabrication tools and knowledge resources. Within this innovation scenario the study is particularly focused on exploring the *early* stages of research and development, rather than phases concerning product testing and marketing.

This thesis provides data from a practice-based study with a technical focus on the development of fabrication concepts based on an underutilised fabrication concept known as Reconfigurable Pin Tooling (RPT). This manufacturing idea has also been described as 'universal' or 'ideal' tooling and has attracted interest from a number of researchers and inventors since the mid nineteen century (Munro and Walczyk, 2007). Although presenting potential advantages compared with conventional production systems, the concept has only been used in very few practical and commercial applications. Developments in digital technologies are now providing the technical foundations for developing new RPT systems and applications.

The practice element of this study features two strands of enquiry. One concerns the development of an RPT system for the production of glass bowls within the researchers' own creative practice. The other practice strand was guided by interaction with a local furniture company, MARK Product, and focussed on the development of an RPT system for shaping upholstery foam. In combination, the two practice elements served to investigate tools, factors, and approaches that are involved when independent practitioners engage in innovation in the context of digital fabrication. Results from both investigations provide new insights into the independent innovation in this field.

Original knowledge contributions from this research include the development of two novel RPT applications with a number of new technical solutions also having been established as a result of this study. Equally, the exploration of the glass RPT concept led to the productions of original artistic output, which is presented as evidence for the creative potential of this RPT concept. Furthermore, the study resulted in the development of a new approach for recording research data in rich media format via an IOS database template. Conceptual knowledge contributions concern concepts and aspects that are relevant to independent innovators operating in the context of digital fabrication, building on the work of Smith and Von Hipple (2005; 2005). Reflections of this study in relation to S-curve theory (Christensen, 1997; Foster, 1986) are also included.

The insights from this research have resulted in a concluding argument which proposes that an innovation toolset, which is combined by several facilitating aspects, can be seen as enabling individual practitioners to *shift* from operating within an individual innovation sphere to a position where they are able to make a valuable contribution in sectors beyond their own practice.

Key words:

Digital Fabrication, Independent Innovation, Design, Reconfigurable Pin Tooling, Prototyping, Tool-making, Reflective Practice, Outsider Innovator.

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1 Introduction

The development of digital fabrication technologies were previously the preserve of a few specialist companies (such as Stratasys and 3D Systems), but over the last decade a number of developments have expanded the opportunities for individual innovators to actively contribute to the development of new design and fabrication concepts.

Initiatives such as FabLabs, the Maker Movement and the RepRap project have helped to serve as catalysts for new opportunities in innovation with digital fabrications techniques and technologies, and helped to stimulate a much wider debate around new models of design, production and consumption. Online networks and forums have enabled the dissemination of a multitude of independent innovator projects. As well as serving as knowledge resources such sites are important sources of inspiration and motivation for others to undertake their own projects.

Also contributing to development of a new 'landscape' in design and production are the convergence of ideas and development tools from other technology driven sectors such as communication, media and computer science. Most significantly these developments include a high level of diffusion of digital technologies, in particular the widespread access to knowledge for constructing both the hardware and software elements of digital fabrication systems.

Appropriation of technologies and innovation approaches from other digitally driven sectors is also increasingly having an impact on the developments in design and fabrication. Of significance in this regard are networked innovation models described as 'commons-based peer production' (Benkler, 2002) - models which are perhaps best known as the basis for the open source software development movement (Raymond, 1999).

As a whole this environment presents the individual innovator with an unprecedented range of development tools and knowledge resources. These opportunities have become particularly evident over the last 5 to 10 years, with a number of projects attracting significant press and investment attention, perhaps best illustrated in the rise of new companies such as MakerBot Industries, Bits for Bytes and Formlabs (Foundry Group, 2011; Mcguirk, 2009; The Economist, 2011).

The maturing and diffusion of this set of technologies has meant that the wider field of digital fabrication has undergone a process of moving from a relatively specialist area, firmly situated with the established manufacturing sector, to becoming much more ubiquitous and widely accessible. This provides part of the background for undertaking this research project at this particular time.

Part of the argument in this study is that these developments are leading to a blurring of disciplines which are allowing individual practitioners to increasingly operate in a multi-disciplinary way, thereby enabling them to innovate independently. A growing number of independently developed digital fabrication systems serve as indicative evidence of these new opportunities (these and other initiatives will be discussed further in the contextual review in this thesis).

While many of these projects are ‘self-build’ versions of commercial equipment, there are also examples of truly original systems being developed, such as those in the FABbot project (Malé-Alemany, 2010). A common theme for many of these projects is that they have been focused on a high degree of novelty without making a significant impact in a commercial context. Through industry engagement and consultation one of this study’s objectives was to develop fabrication systems that, while both novel and innovative, would also have a commercial potential. Furthermore in relation to this objective, it should be highlighted that this research was funded by the European Social Fund with an aim of providing an impact on the regional economy of Cornwall. This funding provided the impetus for working with a local industry partner, MARK Product, to identify and explore commercial ‘real – world’ applications for the RPT concept developed in the context of the furniture design sector.

In summary the field of digital fabrication presents an emerging plethora of opportunities for research, creativity and commerce. This research is seeking to investigate how the access that individual innovators have to affordable and powerful digital development tools and resources can be used to establish new fabrication systems that provide new creative and commercial opportunities.

2 Scope and Rationale of Research

Over the last ten years the field of digital fabrication has been rapidly expanding with independent innovators having a particularly prominent role. These developments, in part, provided the imperative and rationale for undertaking this study.

The researcher's primary aim was to investigate how new opportunities presented to independent innovators impact in the early stages of an innovation sequence, rather than (later) phases concerning commercialisation. Nonetheless, it is recognised that the emerging digital economy, in particular, presents new business models for marketing, distribution and consumption of products. These models are relevant to the context in which the outcomes of this research may be applied and therefore these developments provide part of the context for this project. That said, the core of the study predominately concerns the tools, environment and development methods that are available to the independent innovator for the technical development of new fabrication concepts.

It is also relevant to highlight that many of the tools and development approaches explored in this study are being applied across a wide range of activities that include interaction design, computing and product design. Independent innovation in such wide parameters could clearly encompass a multitude of aspects and it is critical to highlight that this study is focussed on exploring independent innovation of technologies that facilitate the fabrication of *physical* artefacts. More specifically, the practical investigations in this study are located in designer-maker practice and small-scale furniture industry.

As highlighted in the introduction the technical focus of this study is on exploring the underutilised fabrication concept of RPT. The rationale for choosing the RPT concept as the technical focus is that as a relatively underexplored tooling method this principle offered a particularly good opportunity for delivering innovation and also the possibility for generating new technical knowledge.

The theoretical foundation of the study is focused on notions of innovation facilitated by technological developments such as (soft) 'technological determinism' (Chandler, 2000) and S-curve theory (Christensen, 1997; Foster, 1986). Equally, notions of innovation provided by 'users' and 'outsiders' (Smith, 2005; Von Hippel, 2005) were also employed to frame the enquiry.

3 Identification of Knowledge Gap: Research Question and Objectives

The use of digital fabrication technologies in art, design and craft practices have been the subject of numerous research projects as well as being investigated through a number of PhD studies including: Bunnell (1998), Marshall (2000), Cutler (2006), Marshall (2008), and Dean (2009). However, digital design and fabrication technologies have continued to undergo rapid developments, which present on-going research opportunities. Most significantly, these developments include a high level of diffusion of digital design and fabrication technologies. Equally, the knowledge needed for constructing both hardware and software elements for digital fabrication systems has become far more accessible than at the time of the studies mentioned above. Earlier investigations have also predominately focused on creative practitioners' exploration of commercial off-the-shelf digital fabrication technology without considering the potential for individuals to engage in the innovation process of bespoke fabrication systems themselves. In order to provide an opportunity to deliver original knowledge to this area of research, this study focused on exploring these innovation opportunities through a practice-based investigation of the underutilised RPT fabrication concept.

Furthermore, this study sought to explore how individual practitioners can deliver innovation not only from within their own practice, but also to utilise their tools and expertise from this context to contribute in innovation scenarios in sectors beyond their own practice sphere. Searches have indicated that no other PhD study has been carried out in this particular combined research space.

The overarching research question framing this study can by summarized as:

- How can digital fabrication tools and knowledge resources facilitate independent innovation, focussed through an exploration of new applications for Reconfigurable Pin Tooling?

The following objectives have been identified to address this question:

- To investigate how digitally based tools and knowledge resources can be used in the innovation process of new fabrication systems.
- To investigate particular development methodologies that are characteristic of current independent innovation communities.

- To investigate various RPT concepts and develop iterations of systems established by other researchers.
- To develop and test RPT systems for applications informed by engagement with a regional company, and also within the researcher’s own creative practice.
- To contextualise the practical research work within a theoretical framework relating to notions of innovation.

4 The Researcher’s Profile and Motivation

As this research seeks to investigate the potential for the independent innovator to operate in the field of digital fabrication through a practice-base methodology centred on the researcher's own practice, the profile and motivation of the researcher is of considerable importance. Whilst this chapter will outline these aspects, the researcher’s role in the innovation scenario is also further debated in the chapters concerning methodology and models of innovation in the contextual review.

The researcher initially trained as a craft potter after completing a four-year apprenticeship in his native Denmark. In 1991 he moved to the UK where he worked as a production thrower at Dartington Pottery. While at the pottery he became increasingly interested in industrial production methods, and after studying 3D Ceramic Design at Cardiff Institute of Higher Education, he established his own ceramic design consultancy in 1995, working for some of the world’s leading tableware companies. Through years of hands-on design experience in this sector he developed an extensive in-depth knowledge of design and production processes and acquired specialist skills in plaster modelling and mould making.

Fig. 1 *Contour Bowl* (2004) by T Jørgensen, photo: T Jørgensen, 2006.

The researcher first started working with digital technologies in 1996 during a residency at the Hothouse Design Centre, Stoke on Trent. During the early 2000s he collaborated with the University of Plymouth on a number of projects exploring emerging digital production techniques. In 2005 he joined the Autonomatic Research Cluster at University College Falmouth as a Research Fellow. Autonomatic was established with a specific focus on investigating the possibilities of using digital design and production tools as the foundation for new models of creative practice.

Much of the researcher's work in this role has focused on the creative exploration of digital design and production techniques, in particular investigating how new computer interfaces can facilitate more personal and expressive aesthetics in the artefacts created with such tools. These investigations have been integrated in the researcher's own creative studio practice and the resulting artefacts have been featured in many national and international exhibitions, such as *Interface*, (Wynne and Woolner, 2006), *Lab Craft* (Crafts Council, 2010) and *Object Factory* (Cecula and Kopala 2009).

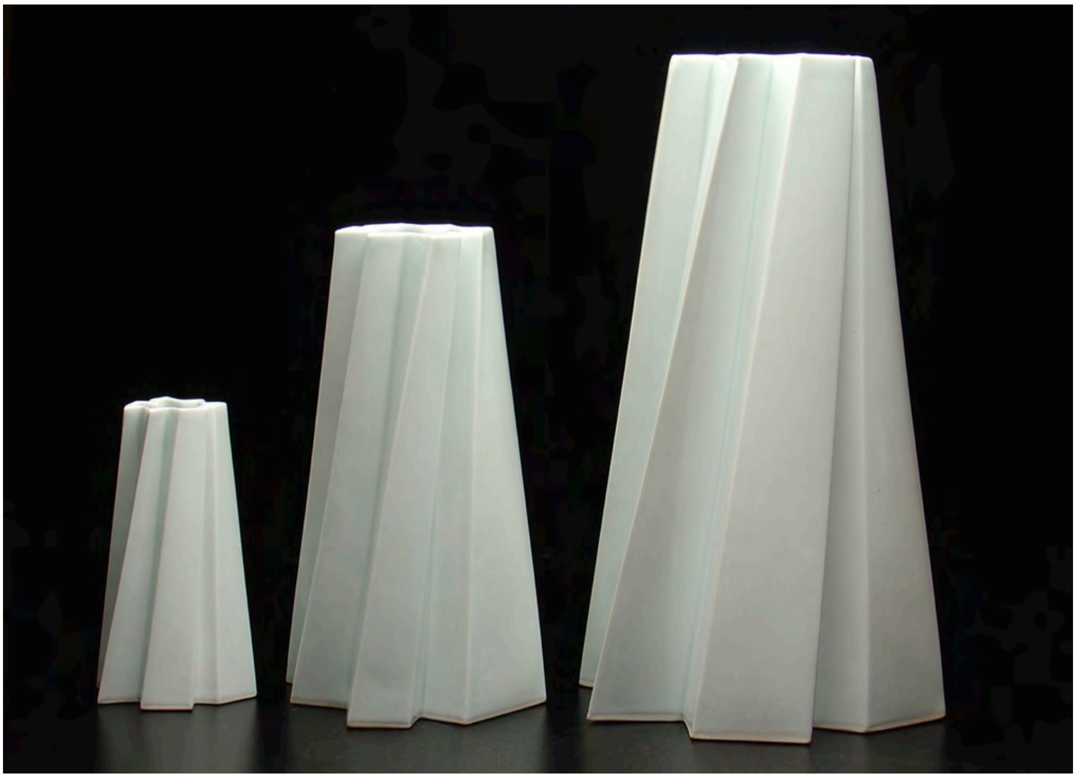


Fig. 2 *Ceramic Origami* (2004) vases by T Jørgensen, photo: T Jørgensen, 2007

The motivation for undertaking this study grew out of the researcher's recognition of new emerging opportunities which enable designers to operate across a number of disciplines to develop bespoke design and fabrication techniques, rather than just explore the creative opportunities with generic commercial equipment.

A long-standing interest in the novel and under-utilized fabrication concept of RPT provided a focus for a practice-based investigation of these new innovation opportunities. A track record as an early adopter/user of digital design and fabrication technologies has enabled the researcher to take a role that could be characterised as a ‘lead user’ innovator (Von Hippel, 1986). Equally, as a creative practitioner undertaking practice-based research in a field which traditionally has been the preserve of specialist engineers, the researcher's position could also be related to the notion of the ‘outsider innovator’ (Smith, 2005). Both the ‘lead user’ and ‘outsider innovator’ concepts will be discussed further in the contextual review.

5 Critical and Contextual Review

The topic of this study encompasses a number of subjects and fields and consequently the contextual review that provided the base for the investigation is somewhat wide-ranging. It starts with a section covering the theoretical base for the study. This is further divided into subsections discussing two key theoretical elements that include tools and technology, as well as discussions on innovation models.

Following the discussion concerning the theoretical basis for this study is a subsection setting out an argument why, in this particular context, ‘access to tools’ is considered by the researcher as one of the key enabling factors for independent innovation. This section surveys the current environment for the independent innovator’s access to innovation tools and knowledge resources. In particular, highlighting the role that the open source concept has contributed to the innovation environment.

The contextual review also includes a section on the technical context. This subsection gives a brief overview of digital manufacturing in general, and a more in-depth review of RPT, which is the particular manufacturing concept that has been chosen as the technical focus for this study. Following the technical context is a review of key examples of self-build, digital fabrication projects. This review was carried out during the early phases of this study in 2011. A section follows which concerns the relevant economic and business context for this study, with subsections on the Digital Economy, crowd funding and the notion of flexible specialisation. A description of the local economic context and industry business partner concludes this section.

It is very important to highlight that the above sections form the core elements of the contextual review as it was carried out at the outset of this study in 2010/2011. However, as this study concerns a very fast developing sector, an update to the initial review has been provided at the end of the contextual review. This update covers some significant developments, particularly in regard to the digital fabrication sector. Throughout this study the researcher has followed these developments closely, and as well as providing a continuous, up-to-date, informed background for the practice elements of the study, this contextual engagement has been instrumental in building up a theoretical framework for study. This framework has been developed on the basis of theories concerning technology S-curves (Christensen, 1997; Foster, 1986; Rogers, 1962). These theories will be discussed in this update and used as the basis to situate this research in conceptual and theoretical terms in the final discussion and conclusion of this thesis.

5.1 Theoretical Foundation for Study

The initial part of this section will outline wider notions concerning tools and technologies, in particular, theories of technological determinism and technology driven innovation cycles. These notions provide key elements of the theoretical foundation for this research.

5.1.1 Tools and Technology

The concepts of tools and technology in the broadest sense are almost inseparably intertwined, or as McCullough notes, 'All tools are a kind of technology' (1998, p.64). Equally intertwined is the development of human culture in general, as Schodek et al. states, 'the development of tools has long been acknowledged as one of the defining characteristics of human evolution. They have served to increase human power, improve precision, and generally enabling devices that have defined our unique ability to make tools used in turn to make other tools' (2005, p.17). Consequently, it is virtually impossible not to acknowledge that tools and technology are agents of change in some way.

Opinions vary among scholars as to what degree tools and technology *exclusively* drives cultural, economic and social developments. Schools of thought that view technology as the main driver can be seen in the theories associated with technological determinism. Chandler (2000) presents a comprehensive overview of these theories, and outlines a number of aspects and variants within this spectrum of thinking. The variants include simplistic theories such as ‘reductionism’ where a view of mono-causal effects of technological developments are separated from a bigger socio-economic picture. A further variant includes ‘technological imperative' - a notion of technology driving unavoidable and irreversible change. Chandler lists some of the most enthusiastic proponents of theories of technological determinism coming from authors such as Marshall McLuhan and Alvin Toffler. McLuhan’s work in particular is based on technological deterministic views, which is illustrated by the well known quote summarising his position as, 'We shape our tools and thereafter our tools shape us' (Grosswiler, 2010, p.73). Chandler presents critical voices of technological deterministic views coming from critics such Lewis Mumford and Ruth Finnegan. Chandler summarises his text by listing the various theories in two main categories of: ‘strong’ technological determinism and ‘soft’ technological determinism. The former position is characterised by a view of technology as the sole cause or driver of socioeconomic conditions. The ‘soft’ technological determinism position encompasses more moderate views of technology as 'an enabler or facilitating factor leading to potential opportunities which may or may not be taken up' (Chandler, 2000).

Key texts on innovation also appear to contain significant elements of technological determinism. In particular, the often referenced work by Russian economist Nikolai Kondratiev, who was working in the 1920’s. Kondratiev theorised that the economy of the industrialised world since the first industrial revolution has been characterised by long term ‘cycles’ or ‘waves’ lasting about 50 years (Freeman and Louçã 2002). He proposed that these waves consist of four periods: 'recovery, prosperity, recession and depression' (Freeman and Louçã, 2002; Smith, 2005, p.49). Joseph Schumpeter expanded on Kondratiev’s theory by arguing that these waves are driven by innovation based on technological advances (Freeman and Soete, 1997). In this theory the initial wave is considered to be the first industrial revolution in Britain in the late eighteenth and early nineteenth-century, particularly concerning the mechanisation of the textile industry, iron smelting and innovations in the use of waterpower. According to this theory three other waves then followed based on innovation in various groups of technologies that created new techno-economic paradigms, as described in detail by Freeman and Louçã (2002). Freeman and Louçã further argue that we are now in the fifth Kondratiev’s wave that is based on innovation in information and communication technologies (ICT). In particular, the development of the personal computer (PC), the Internet and telecommunications. This wave is considered to have a starting point in the early 1980’s. Smith (2005) argues that it is especially during periods of recession and depression that we are most likely to see new inventions and innovations as the economic return of previous technological discoveries gets exhausted. According to Schumpeter’s interpretation of Kondratiev’s theory we should now be entering such periods (Freeman and Louçã, 2002; Kumar, 1995).

Other scholars (Fagerberg et al., 2006) concur with Kondratiev and Schumpeter on the notion of innovation and technology following cycles or waves, but propose other starting points, lengths of waves and groups of technologies concerned. Equally, such cycles are also the subject of regional and national variations (Freeman and Louçã, 2002; Smith, 2005). Commentary in the current debate concerning the developments in digital fabrication also frequently appear to be technologically deterministic in tone, particularly in texts with enthusiastic beliefs in technology as the main driver of change. Examples of such positions could be recognised in the writings of Gershenfeld (2005) and Sterling (2005).

The researcher's own position corresponds with such views, and a 'soft' technological deterministic stance has been adopted within this research by recognising the opportunities that digital technology (and specifically the diffusion of digital technology) presents as an enabler and facilitator for individual practitioners to explore creativity and innovation. Furthermore, this research is orientated towards a scenario where a 'technology push' dominates over a 'market pull' in terms of the principal driver of innovation (Smith, 2005, pp.119–132). Such a position could also be seen as having a technological deterministic bias.

5.1.2 Innovation Models

This section first outlines various theories relating to the process of invention and innovation. A rationale for focusing on a 'lead user' or 'outsider' innovator positions (Smith, 2005; Von Hippel, 2005) in this study is also provided.

In order to discuss the particular innovation in models that are relevant to this study, it is useful to determine a working definition of innovation. Smith (2005) provides a comprehensive overview of the concept in relation to notion of invention. Smith states: 'Invention involves new ideas, new discoveries and new breakthroughs' (2005, p.6). Smith clarifies that while invention is the basis for innovation, the latter is concerned with the application and exploitation of discoveries or as Smith notes: 'Quite literarily innovation is about bringing the inventions out of the workshop or the laboratory and getting them ready for market' (2005, p.6). So while invention can (and frequently does) form a part of the innovation process, the process itself can be broken down into a number of steps, as illustrated in Fig. 3.

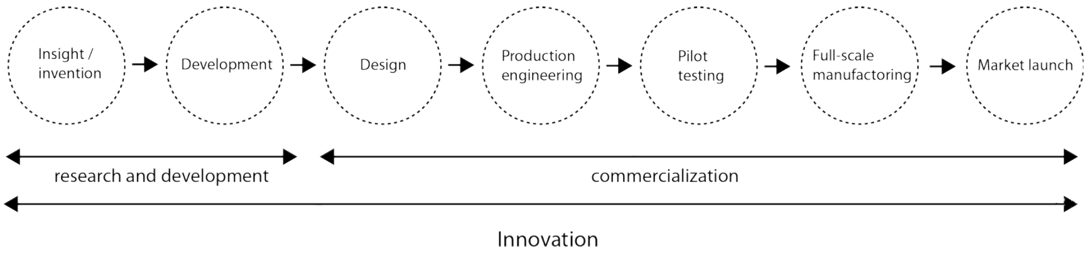


Fig. 3 Generic model of the innovation process, after Smith (2005).

After the innovation sequence a further stage can occur — that of ‘diffusion’. Diffusion is the large-scale adoption of an innovation, which can have a significantly wider impact on a market sector. The impact of the dramatic growth in the market for personal computers during the 1980s, and the influence of the Mini’s (1959) front wheel drive on the automotive industry are both examples of diffusion presented by Smith (2005, pp.6–8). It could be argued that there are signs that a significant level of diffusion is now starting to occur in sectors of digital fabrication (Stevenson, 2011).

As previously mentioned, inventions are ‘the seeds’ for the innovation process. Smith analyses invention as a process of ‘non-linear’ idea generation resulting in an ‘insight’ and provides four scenarios for this insight to happen, 'Association, adaptation, analogy and serendipity' (2005, pp.86–88). In this study the ‘association’ category is of particular interest as will be evident in the description and discussion of the two practice strands. The association scenario involves bringing two unconnected fields together to solve a problem or create new solutions.

Smith continues to identify the sources of such ‘insights’ as: 'individuals, outsiders, users, corporate undertakings, spill overs, and process needs' (2005, pp.85–96). The first three of these categories are of particular relevance to this study and the premise of this research is that the increased access to tool and knowledge resources facilitates increased levels of innovation from these particular sources. While Smith chooses to separate these categories, a significant degree of overlap between them would seem obvious. By ‘individuals’ Smith refers to the archetypal public perception of the independent inventor, a concept also described by Pursell (1994, p.38). The outsider category is characterised by innovators who come from fields that are different from those which they innovate in. The ‘user’ category mainly refers to the large body of work on ‘user innovation’ by Eric von Hippel. This work is generating increasing interest, especially in relation to the increased access to digital tools and knowledge resources. In *Democratizing Research*

(2005), Von Hippel presents a large body of research that includes empirical evidence for the advantages of user-centred innovation in contrast to the traditional manufacturer-centred innovation. Von Hippel advocates user innovation very broadly, but it is important to highlight that by the term ‘user’ Von Hippel not only describes individual end-users / consumers, but also uses the term to include companies and highly skilled professionals. In this regard Von Hippel provides examples of designers of integrated circuit boards, hospital surgeons and even large companies, such as Boeing. Von Hippel clarifies that Boeing, in its core business as a producer of aeroplanes, *use* machine tools, but as the company also carries out in-house development of metal forming equipment, Boeing can also be classified as a user-innovator (2005, p.3).

Von Hippel is also credited with developing the notion of the ‘lead user’ (1986). This theory is based on empirical evidence that identifies a proportion of users which are most likely to undertake innovation, this group is defined by two distinctive characteristics: '(1) They are at the leading edge of important market trend(s), and so are currently experiencing needs that will later be experienced by many other users' and '(2) They anticipate relatively high benefits from obtaining a solution to their needs' (Von Hippel, 2005, p.22). He also presents evidence that ten to forty present of all users are involved with some sort of product modification, which could be classed as innovation, and argues that among this group of ‘user innovators’, the vast majority will have lead user characteristics (2005, pp.19–31).

A similar concept to that of Von Hippel’s ‘lead user’, is presented by Leadbeater and Miller (2004). In this text the authors present the notion of the ‘professional amateur’ — the ‘Pro-Ams’ describing the concept as: 'amateurs who work to professional standards' (2004, p.12). The authors describe how new networking technology has provided a foundation for the rise of this concept. Leadbeater and Miller ague for the wide-ranging benefits this concept can provide to the wider society, with examples and evidence from both qualitative and quantitative research.

Overall, there is acknowledgment by many scholars (Pursell, 1994; Smith, 2005) that external or independent ‘actors’ have a strong potential for providing a significant contribution to the innovation process, particularly in the early phases of this sequence. Pursell states: 'almost per definition new products, processes and attitudes must come from outside the status quo' (1994, p.38). However, the conditions and opportunities for ‘individuals’ to contribute to the innovation process have varied significantly over time. Many authors (Leadbeater and Miller 2004, p.51; Von Hippel 2005, p.21; McLuhan and Fiore 1967) highlight the important role that independent *amateur* inventors/innovators played in the first industrial revolution. However, Freeman and Soete (1997) describes how the domain of invention and innovation gradually shifted from individual, craft-trained practitioners to becoming an increasingly specialised activity based on scientific knowledge. They describe that during twentieth-century, innovation predominantly became the domain of corporations, organised in specific R&D departments. Freeman and Soete argue that the move to separate R&D from production was a result of the emergence of inflexible mass production systems, which were badly suited to accommodate innovation by individuals involved in the actual production process (Freeman and Soete, 1997). Pursell (1994) highlights how increased science based inventions impacted on which actors were able to be involved in innovation. Quoting Gorge Wise, he highlights how in the ‘high tech’ areas of development during the early part of the twentieth century, such as electricity and radio, American engineers outperformed their British colleagues due to their science based university training. Whereas the shop-trained British engineers with their applied and practical knowledge remained superior when it came to the development of mechanical systems (Pursell, 1994, pp.56–57). Freeman and Soete concur by stating that patents filed by individuals in the field of mechanical engineering still form a significant proportion of the overall number of patents filed in this field. In contrast, inventions in electronics and chemicals has become largely a domain for corporate development, with a low and declining contribution from individuals (1997, p.16).

Smith argues that there are now signs that the sources of innovation are increasingly returning to individuals and small companies (2005, p.97). However, the opportunity for individuals to participate in innovation appears to be dependent on maturity and diffusion of a particular technology.

The basis of most digital fabrication systems is a generic Computer Numerically Controlled (CNC) operation, and the information and components needed for constructing such systems are now so widely diffused that scientific or theoretical training is no longer needed to participate in innovation with this technology. This means that individual practitioners from a wide range of backgrounds and disciplines have the opportunity to utilise their particular knowledge and experience to engage in both process and product innovation.

5.2 Access to Tools, Knowledge and Support

This section outlines the development of tools and knowledge resources in the particular sector of this study and reviews the effect they are having on current developments. Parallels will be made with current developments and historical examples where independent practitioners have lead the innovation process through increased access to development tools — notably during the first industrial revolution and the development of the PC during the 1970's. A review of the open source development model, which is also recognized as one of the key drivers of the current developments in digital fabrication, is provided at the end of the section.

5.2.1 Access to Tools

In order to be able to innovate in any given field it is fundamental for the inventor or innovator to have tools and resources to do so. Von Hippel (2005) argues against the traditional industrial model of centralising innovation on a few selected individuals as hugely inefficient and provides the example of top designers in the automotive industry as such a model (Von Hippel, 2005, p.14). He advocates a greater democratisation of the innovation process by engaging the *users* of products and technology in this process. He also highlights the diminishing cost of high-quality innovation resources such as powerful programming tools and sophisticated Computer Aided Design (CAD) programs and states: 'users ability to innovate is improving radically and rapidly as a result of the steadily improving quality of computer software and hardware, improved access to easy-to-use tools and components for innovation and access to a steadily richer innovation commons' (Von Hippel, 2005, p.13).

The current scenario with its diffusion of technologies and the increased access to development tools that enable independent practitioners to innovate has parallels with a number of historical examples. One example could be seen in the origin of key developments that have shaped many of today's pervasive digital technologies. These developments have been linked to a particular shift in expanding the access to early computer technology from groups of specialists to a much wider spectrum of innovators and entrepreneurs. In particular, it is useful to review the creation of the PC industry in Silicon Valley in the mid 1970's (Cringely, 1996; Smith, 2005). The researcher contends that there are a number of parallels that can be drawn between this development and the one that now appears to be underway in the field of digital fabrication.

The first electronic computers dates back to the early 1940s with projects in Germany, US and Britain, which were mainly government funded for militarily applications (Freemann and Soete 1997). The development and application of computers grew significantly throughout the 1950's and 1960's, pioneered by companies such as IBM and Remington Rand (Freeman and Soete, 1997). However, these mainframe computers carried a very high cost and had complex technical operating processes (Cringely, 1996). Consequently innovation and development remained the preserve of a small number of specialist scientist and engineers (Schodek et al., 2005).

It was not until the arrival of the microprocessor that powered the first affordable (and primitive) computers such as, the Altair 8800 in the mid 1970's that the access to emerging computer technologies became more widely available for non-specialist users (Cringely, 1996). These early PCs served as experimentation tools for a growing number of amateurs and technology enthusiasts including those that formed groups such the Homebrew Computer Club (Cringely, 1996; Roszak, 2000). It was groups like these that fostered and shaped the development of the early computer industry in Silicon Valley, which helped to drive the emergence of a technological and economic revolution (Cringely, 1996). Smith (2005, p.92), amongst others, provides the example of Steve Jobs and Steve Wozniac's initial position as 'amateur outsiders' to the established mainframe computer industry, and argues that this position was a key contributing factor in their success as innovators. Roszak's essay, 'From Satory to Silicon Valley' (2000), describes the Californian counterculture of the 1970s, which appear to have striking parallels with the characteristics of the communities that are currently engaged in experiments with 'home-brew' digital fabrication systems. The elements of confident resource-fulness through a DIY approach appear to have distinctive similarities with contemporary developments. This approach was particularly evident in the influential magazine of the 1970's counterculture, *The Whole Earth Catalogue*, which had a strap line stating: 'Access to Tools' (MoMA.org, 2011). Through articles and post order listing of both 'high and low tech' equipment, the publica-tion's goal was, 'to make a variety of tools accessible to newly dispersed counterculture communities, back-to-the-land households, and innovators in the fields of technology, design, and architecture, and to create a community meeting-place in print' (MoMA.org, 2011).

The development of the PC industry that followed enabled an ever-increasing access to cheaper and more powerful computer tools that in turn enabled other individual entrepreneurs to innovate. The result was the rapid growth in digitally driven creative output and innovation, particularly in the media sector and evident in the arrival of desktop publishing. In turn these developments resulted in establishing entire new professions, business sectors and models, especially characterised in the boom of Internet based services and content in the 1990's (Freeman and Louçã, 2002).

The impact of digital technologies has to date been far less widespread and profound in sectors focussed on the fabrication of physical artefacts. Although digital fabrication technologies have been used for a considerable time, they have mainly been employed in specific specialist applications and sectors, such as the automotive, medical and architectural sectors (Schodek et al., 2005). Furthermore, the innovation and development of new digital fabrication tools have remained firmly with specialists from the fields of science and engineering working in R&D departments in commercial companies and academic institutions.

Just like the impact that the widespread access to affordable and powerful computer tools have had on driving innovation in media and communication, there are indications that a similar scenario is in the process of transforming the world of fabrication. Many authors, including Gershenfeld (2005), Pescovitz (2008) and Sterling (2005), have predicted that digital technology will have an equally dramatic impact on the world of design and manufacture of objects, as it has had on the sectors of communication, media and print.

Gershenfeld's book, *FAB: The coming revolution on your desktop – from personal computers to digital fabrication*' (2005), is considered to be one of the most influential texts in recent years in regard to innovation by individuals in digital fabrication. In the text Gershenfeld, a professor at MIT and director of The Center for Bits and Atoms, describes his frustration over 'the artificial separation of computer science and physical science' (2005, p.4). As a response, he initiated a class at MIT in 1998 called, 'How To Make (almost) Anything', where students were encouraged to work in a cross disciplinary way and explore personal interests by making things they had long dreamt of creating. To facilitate their exploration, a collection of flexible digital fabrication equipment were made available, including laser cutters, CNC milling machines and rapid prototyping equipment. Gershenfeld describes how this newfound access to powerful fabrication tools fuelled an explosive interest among the students to create. The aspect of physical fabrication was integrated with the development of bespoke electronics and computer code linking both physical and digital elements in complete functioning systems, thereby bridging what Gershenfeld describes as, 'significant divide between the access to tools for fabrication and instrumentation' (2005, p.13).

The concept of a physical lab with equipment that integrates the fabrication of physical parts with electronics and computer code was titled a 'FabLab'. Gershenfeld explains the term, 'can mean a lab for fabrication, or simply a fabulous laboratory' (2005, p.12). This highly successful concept led Gershenfeld to initiate independent spinout versions of the lab. This initiative has been very successful with over a 100 labs now existence around the world (Charny, 2011, p.58). The FabLab movement has attracted a high level of publicity and has in some way been the banner bearer for community involvement with digital fabrication. However, FabLabs are not alone in this work, other community facing workshops are also contributing to with impact in this regard, including the Techshops (TechShop Inc, 2010) and Maker spaces in the US, and initiatives, such as Metropolitanworks (London Metropolitan University, 2011) in the UK.

Another very significant element which has contributed to the expansion of the opportunities for individuals to innovate in digital fabrication has been the growth of the commercial bureau sector, with an increasing number of companies offering bespoke digital fabrication. Such services are now widely available locally, enabling individual inventors and innovators to make prototypes and components at relatively low cost without having to invest in their own fabrication tools. In the Cornish and South West region examples of such companies include: Luffman Engineering (Luffman Engineering, 2011), LaserMaster (LaserMaster Ltd, 2011) and Laser Industries (Laser Industries Ltd, 2011). These companies have invested in expensive industrial grade equipment that has the capacity to produce highly accurate one-off pieces from digital files.

This issue of innovators' need for access to prototyping tools capable of creating parts of high accuracy is one that has played a very important part in previous cycles of innovation. It is generally acknowledged that the development of machine tools, such as the metal lathe, which in turn enabled the production of highly accurate machine parts, was a fundamental element in the innovation boom of the first industrial revolution. Samuel Smiles in *Industrial Biography: Iron Worker and Tool Makers* (1863) highlights how the innovators of this period at times had to battle with low levels of accuracy in the prototypes of new inventions, which before good quality machine tools emerged were mainly created via hand skills. Smiles describes how James Watt, working on the steam engine cylinders, despairs over the low levels of precision which was holding back the development of his inventions. Smiles remarks, 'accuracy of fitting could not be secured so long as the manufacture of steam-engines was conducted mainly by hand'. And concludes that, 'it was not until the invention of automatic machine-tools by mechanical engineers, that the manufacture of the steam-engine became a matter of comparative ease and certainty' (Smiles, 1863, pp.180–181).

Current initiatives have been undertaken which have sought to facilitate a better linking of individual designers and innovators with digital fabrication bureaus. An example of such an initiative is the *100Kgarages* (ShopBot Tools, Inc., 2012). The *100Kgarages* site provides an online forum and a directory of the services of a network of digital fabricators, with listing of both commercial companies and community facing workshops.

5.2.2 Open Source

Although this particular research project is not structured via an open source model, it recognises the open source movement as one of the main drivers of the current developments in digital fabrication. The open source development model has provided many of the key software and hardware tools for independent innovators as well as models for peer group support, consequently it is relevant to include the open source concept in this contextual review.

It is perhaps not surprising given the long history that digital technology has in sectors such as, computing, communication and media that the vast majority of the development tools and approaches, which are now making an impact on the digital fabrication sector, have been appropriated from these fields. One of the most a significant drivers of such appropriation in recent years has come from the open source movement. The central concept of open source is a model of development where a computer program is created by a community of unpaid developers who, out of personal interest, contribute to the development of the project. The source code of the software is made public for everyone to freely use, modify and improve.

Open source can also be described as 'commons-based peer production', a notion which encompasses a spectrum of non-hieratical collective innovation models (Benkler, 2002). The open source concept has also frequently been described as similar to the structure that underpins academic research, where scholars freely reveal the details of their research in order for other scholars to build on and benefit from. Von Hippel presents other examples of common-based peer production such as, the furnace technology of nineteen-century English iron industry, and also the collective improvement of Trevithick's steam engine design by the Cornish mining engineers (Von Hippel, 2005, pp.78–79).

The term 'open source' was first coined in 1998, but the concept had by then already been emerging for some time among the 'hacker' community in the US in the 1990's as a reaction to the commercial, proprietary (closed) model of software development. In this regard, it is important to clarify the notions of 'hacking' or 'hacker' as the terms carrying two distinctly different meanings. The terms have frequently been used to describe illegal activity, usually an unauthorised breach of computer or communication security. The hacker community generally distance themselves from such activities and label it as 'cracking'. The original definition of 'hacker' or 'hacking' describes a person or activity involved with the appropriation of technology in new and innovative uses, usually within a subculture community (Raymond, 2001). This research adopts this original definition of these terms.

Raymond's text, *The Cathedral and the Bazaar* (Raymond, 1999), concerning the open source movement, is considered to be one of the most influential and remains the most referenced (Google Scholar, 2011). Raymond, who is one of the founders and leading proponents of the movement, outlines the concept in detail with a particular focus on the development of Linux as a main case study.

The open source concept has been frequently associated with the term 'free' and some now include the notion as a part of the overarching category of Free and Open Source Software (FOSS). Raymond disagrees with this categorisation but acknowledges the heritage of the open source concept as growing out of a community of hackers associated with the Free Software Foundation led by

Richard Stallman. Raymond concurs with Stallman's clarification of the term 'free' in the context of open source as, 'free as in free speech, not as in free beer' (Free Software Foundation, 2011a).

Raymond clarifies that *free* in terms of open source means that while it is free for anyone to use, modify and improve the source code, a structure of ownership still remains. Raymond outlines that in practical terms this mean that the founder of an open source project is generally recognised by the community of developers as the leader of the project (Raymond, 1999, p.73). Project leaders can choose to release their projects under a number of various licences, which specify the terms of condition under which the code/information may be used. One of the more commonly used licenses is the GNU General Public Licence (GPL) (Free Software Foundation, 2011b). Other licences that are also frequently used for commons based projects include, the LGPL (Free Software Foundation, 2007), which have less strict conditions; the BSD (The FreeBSD Foundation, 2011) and the newer Creative Commons (Creative Commons, 2011) licence (Laurent, 2004). The latter offer many types and levels of licences as an alternative to conventional copyright and patent laws.

While for some using an open source or commons-based development model is a pragmatic and efficient way of organising innovation, others have a much more political and ideological view of the concept, usually coming from a strong anti-capitalist position. This agenda is also present in some of the commentary of open source projects concerning digital fabrication. Examples of such views can be seen in Carson (2010), Söderberg (2010) and Bauwens (2005).

Raymond is clearly firmly in the pragmatic camp in regards to commercial application of the open source innovation model. In the 'Magic Cauldron' chapter (2001, pp.113–168) Raymond outlines the economic impact of an open source approach and presents a number of business models of how this development method makes good commercial sense. Raymond states that like any other tool, software has two types of value, a 'sale value' and 'use value'. Raymond argues that the *open* nature of open source software make sale value hard to achieve (however, this has been shown to be different from open source projects concerning digital fabrication). Instead, Raymond notes that it is the productivity aspect of the tool that should be the focus of business activity. Among several possible models for commercial exploitation, Raymond highlights that open source can be used to gain a professional reputation, with the potential for employment or paid consultancy work. Raymond also states that the concept can provide an opportunity for growing interest and market penetration very quickly.

While many of the open source software tools that have been developed primarily for Internet based applications could initially be viewed as having little direct impact on the field of digital fabrication, they still provide a very significant impact on the development of the overall infrastructure of the digital economy, which is likely to constitute an increasing important context for digital fabrication. Equally, the universal nature of digital data means the software tools developed in one specific context can relatively easily be employed in other applications than the one originally intended.

The programming language Python (Python Software Foundation, 2011) is a good example of such appropriation of open source software. Python was initially developed predominantly as a scripting language for server side web applications but is now being widely adopted for use in applications for digital fabrication and 3D modelling. The commercial modelling program Rhino 3D (Robert McNeel and Associates, 2012), which have a large user base in the digital fabrication community, has recently announced that it is adopting Python as its main scripting language. Equally, Python is also the scripting language behind Skeinforge (Skeinforge, 2012), which is the software for the open source digital fabricator RepRap (the RepRap project will be covered later in this review).

The Arduino (Arduino, 2011) microprocessor hardware module, which was initially developed in the context of interaction design, is another good example of open source technology that has been appropriated in the field of digital fabrication. The Arduino's intended application as a user-friendly electronic/digital prototyping module has meant that it is has also found extensive use as an integral part of the 'toolbox' of self-builders exploring digital fabrication. A particularly innovative example of such use can be seen in the CNC controlled tattooing machine, *Auto Ink* (Eckert, 2010).

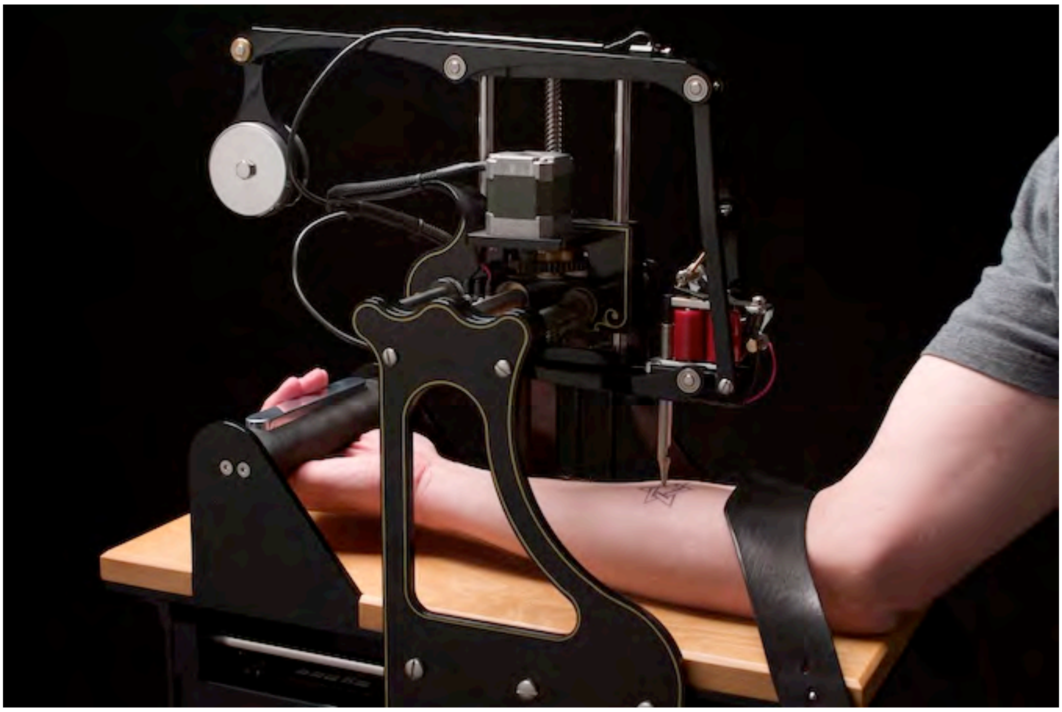


Fig. 4 *Auto Ink* (2010) by Chris Eckert, photo: C. Eckert, 2011 (image reproduced by kind permission of C. Eckert).

The capability of the Arduino unit is further extended by its coupling with the scripting language Processing (Fry and Reas, n.d.). As an integrated hard and software unit these two elements provide a powerful and easy to use platform for prototyping in digital fabrication.

Although many of the FOSS tools that are now making an impact in digital fabrication were originally appropriated from computer programming and interaction design, tools specific for design and fabrication are also being developed with the open source model. Capable design software developed with this approach include the 2D drawing program Inkscape (Courtenay and Owens, n.d.), with 3D CAD programs including Blender 3D (Blender.org, n.d.) and OpenSCAD (OpenSCAD, n.d.).

Increased competition (partly from open source programs) has also meant that commercial CAD software has become much more affordable. In many cases companies offer a lower specification or *light* version of their main programs for free or at a very low cost in order to establish a wider user base. Google Sketchup (Google SketchUp, n.d.), netfabb Studio Basic (netfabb GmbH, 2011) and Autodesk's recent 123D (Autodesk, Inc., 2011a) suite of software tools are examples of free software programs which forms a part of such strategies. Equally a number of free online CAD Apps are also emerging, typically as extensions of services being provided by digital fabrication bureaus such as Shapeways (Shapeways, Inc., 2011).

Companies making commercial CAD programs are also increasingly supporting user contribution by having scripting facilities within the programs to facilitate the creation of custom modules and add-ons. User contribution is often further encouraged by the companies hosting online forums to build up a community of contributors. Such contributions from individuals within a centrally controlled structure is known as *peer production* rather than *commons-based peer production*. A good example of such initiatives is Rhino 3D's parametric scripting module Grasshopper (Davidson, 2012). This module created by David Rutten (who is still the only official developer/programmer), is available as a free extension to the main (commercial) modelling software and has seen an explosive growth in users. A good example of user created Grasshopper add-ons is Daniel Pinker's Kangaroo (Piker, 2011a) module, which extends Grasshopper with live 3D physics simulations, while his Lobster (Piker, 2011b) tool enable inverse kinematic control of five and six axis robots.

Grasshopper has now established a key position as a visual scripting platform for integrating 3D modelling with digital fabrication. The module's user base is wide-ranging and the software has been the key development tool for large commercial architectural projects as well as experimental systems created by individuals.

5.2.3 Access to Knowledge and Support

While having access to development tools is one of the fundamental aspects to enable innovation, the knowledge of how to use such tools is perhaps just as crucial. In the emerging *landscape* of innovation in digital fabrication the growth in knowledge resources which provide support for the use of new these development tools is maybe equally as influential as the actual tools.

Clearly peer group support, either directly or indirectly, is the fundamental basis of projects organised with the common-based peer production model. As this method of development is being appropriated from the original hacker culture, so are the practices of providing peer group support. Raymond describes how this culture operates on a basis of free peer group support. He argues that such an altruistic activity could be viewed as following age-old social models based on a 'gift culture'. Raymond explains that the hacker community is organised on the basis of a 'reputation game' where the social status of each individual is based on what individuals provides to others rather than accumulated material wealth. Raymond also highlights the purely social aspect of hacking and the process of providing support to others in this community as a way of social interaction (1999). In practical terms online forums typically facilitate such support and knowledge. Such forums have also emerged in relation to digital fabrication, with CNCzone (CNCzone.com, 2011) and Rhino Fablab (Gonzalez, 2011) being examples of such subject specific sites.

As already acknowledged in this review, many of the current developments in user driven innovation in digital fabrication are being lead by a resurgent DIY culture; a culture now commonly known as the 'Maker Movement' (Anderson, 2012). This movement could be seen as another cycle in a long lineage of DIY culture. Atkinson outlines some key features in the history and nature of this culture and provides a taxonomy for the various categories under this label of activity. Atkinson notes that elements of peer support are also a feature of this culture, and particularly evident in DIY activities in Britain following the Second World War (2006, p.4). Significantly, Atkinson also provides sources which indicate that the boom in DIY during the 1950s can largely be attributed to technological developments which made easy-to-use materials and tools widely available (2006, p.6). He also notes the many magazines, books and TV programmes, which over the years, have played a pivotal part in providing know-how to DIY practitioners.

Some of the knowledge resources that are supporting the current generation of DIYers to explore digital fabrication follow the established tradition of DIY 'how-to' guides. Launched in 2005, *The Make Magazine* (Woodward, 2005) has a format that fits into a lineage of DIY magazines, such as *Do It Yourself*, *Popular Mechanics* and the US based *Popular Electronics*. *The Make Magazine* (or *Make*), which exists both in an online and printed format, has been a particular influential publication for the Maker Movement's exploration with digital fabrication. Another significant contribution from *Make*, is the publication's initiative to establish Maker Faires (Maker Media, Inc, 2011) events. These public fairs have become hugely popular and have attracted sponsorship from large companies, such as Microsoft, Microchip Technology and Texas Instruments (Dean, 2012).

Fig. 5 Front cover and content page from the *Make Magazine*, volume 21 (Reproduced with kind permissions from Make Magazine)

Make's current position in the current DIY innovation community could be seen as having distinctive parallels with the role that the previously mentioned *Whole Earth Catalogue* played in the development of the personal computer industry in the 1970s, although there are some differences in the tone of the two publications.

The online forum, *Instructables* (Autodesk, Inc., 2011b) is another leading knowledge resource for the DIY community that is currently exploring digital fabrication. *Instructables* is completely driven by user contributions with two million registered members providing approximately 55,000 how-to guides, including projects concerning DIY digital fabrication (Dean, 2012). The site was established in 2005 by MIT graduate Eric Wilhelm, but was sold to Autodesk in August 2011. Autodesk is one of the world's leading suppliers of 3D design software such as Autocad and 3D Studiomax (Autodesk, 2011). This sale could be seen as further evidence of the growing interest that the DIY/Maker-Movement community is generating in the commercial digital design and fabrication sector.

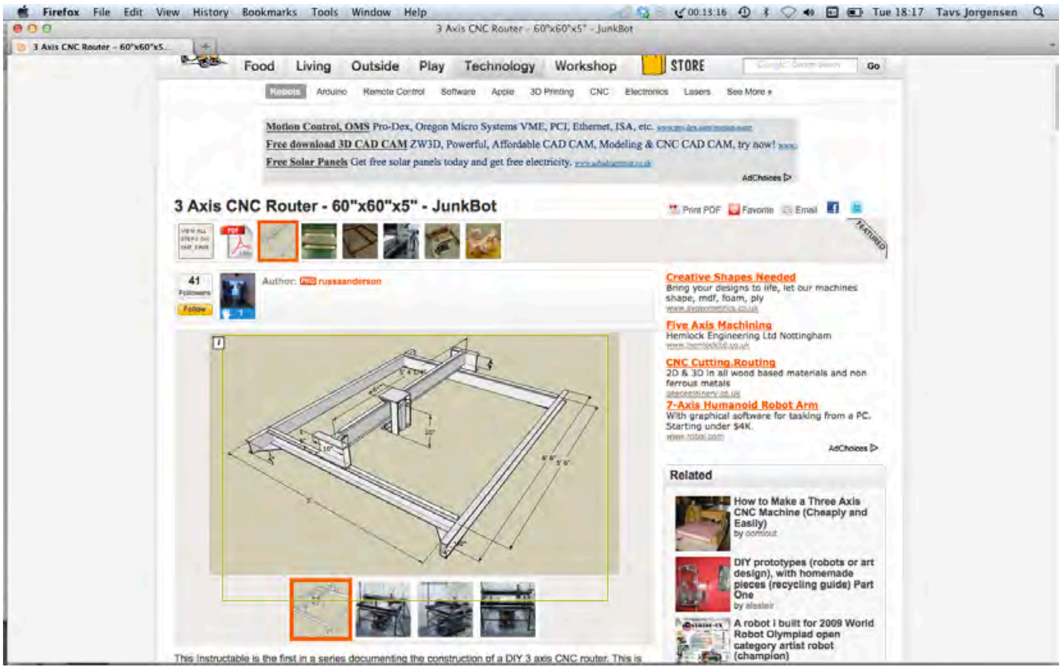


Fig. 6 The Instructables website with example an example of a CNC project, ‘JunkBot’ by Anderson (2008).

While the role of online communities perhaps has to be recognised as currently the main source for providing knowledge for individual designers and entrepreneurs’ explorations of digital fabrication, the role of *physical* spaces in providing peer group support is also likely to be significant. While the FabLabs and other community workshops serve an important function in providing access to tools, they have an equally important role as physical spaces for social interaction and knowledge exchange.

While the FabLab movement, with its particular focus on digital fabrication, is a relatively recent phenomenon, the concept of having physical spaces for DIY groups exploring technology has a very long tradition. Such spaces played an integral part of the hacking culture, and before the advent of affordable personal Internet connections it was the main way for computer enthusiasts to interact socially and exchange knowledge (Levy, 2010). Such spaces have existed since the 1970s under a variety of names, but are now most commonly known as ‘hackerspaces’ or ‘hacklabs’. Today there are hackerspaces all over the world, *hackerspaces.org* provides a growing list of such communities (HackerspaceWiki, 2011). *Hackerspaces* typically have a core focus on computer programming but also encompass a wide range of experimental activities with a broad range of new technologies. This broad focus provides hackerspaces with a user base with a diverse range of skills, and this multi-disciplinary peer group could be seen as one of the key strengths of the hackerspace concept. The contribution that these spaces can provide in terms of support for innovation is documented by Bre Pettis in 'Made in My Backyard' (van Abel et al., 2011), where he charts the development of the Makerbot RepStrap.The New York hacker collective, NYCResistor (which Pettis was a founding member of), can, in this description, be seen as playing a pivotal role in the innovation process, utilising a number of different skill and knowledge bases from the NYCResistor group.

The importance of physical and social interaction with peers to support innovation can be seen in examples from other cycles of innovation, which have previously been noted in this review. Cringely (1996) and Roszak (2000) both highlight DIY technology groups such as the Homebrew Computer Club, which, during the 1970's, played an instrumental role in fostering early experimentation with personal computers. Another example that illustrates the importance of such peer groups can be seen in accounts from the first industrial revolution where clubs such as the Royal Society for the encouragement of Arts, Manufactures and Commerce (RSA) and the Luna Society provided a forum to exchange ideas within a multi-disciplinary group of innovators and scholars such as Erasmus Darwin, Josiah Wedgwood and James Watt (Uglow 2002; Leadbeater and Miller 2004, p.51; Pursell 1994, p.45).

In conclusion, creating a digital fabrication system requires knowledge from a range of fields such as: computing, mechanical and electrical engineering. Consequently, innovating in this field will have to rely on a multi-disciplinary approach. The combination of both new and traditional knowledge resources present unprecedented opportunities for individuals to operate in such a multi-disciplinary space, drawing on an equally unprecedented level of peer group support.

5.3 Technical Context

This section provides a brief overview of digital fabrication, which is the wider technical context for this research and locates this project within a taxonomy of digital production methods. Then follows an extensive review of the history and use of the RPT concept which is the core technical fabrication focus for this study

5.3.1 Digital Fabrication Overview

Digital manufacturing techniques can be categorised in three main sub groups: ‘additive’, ‘reductive’ and ‘formative’ methods. The reductive category includes milling, lathe cutting, laser cutting, water jet cutting, punching and hot wire cutting CNC based equipment.

Digital manufacturing has its roots in the development of the Jacquard loom in the 19th century (Hobsbawm, 1988). Further significant development came in the early 1950’s with the development of CNC milling, but this technology also has a lineage that stretches much further back to machine tools of the mid nineteenth century. Schodek et al. lists the ‘Lincoln’ milling machine of 1855 and the ‘Bowne and Shape’ machine of 1860 as predecessors of the modern CNC milling machines (2005, pp.19–18). However, there are also striking similarities with Whitworth’s 1840 patent for a ‘Self Acting Planing Machine’ and designs of modern CNC milling machines.

The concept of using electronic computers in collaboration with manufacturing tools was first explored by a team of researchers at MIT in the early 1950s. A system consisting of a Numerically Controlled (NC) milling machine operated via computer instructions on punch cards, was first presented in 1952 (Callicott, 2001, pp.48–49; Schodek et al., 2005, pp.18–19). Through the 1960s and 1970s the use of NC and CNC milling grew rapidly and the technology played an important role in developing the concept of Flexible Manufacturing Systems (FIS), a concept that is also related to the notion of ‘Flexible Specialisation’, which is argued by authors such as, Kumar and Piore and Sabel (1995, 1984), as an alternative to the Fordist and Taylorist mass-production models. However, the development and use of CNC milling remained largely the preserve of specialist engineers until the diffusion of the technology was helped by the arrival of the Personal Computers (PC) (Callicott, 2001, pp.3–5; Schodek et al., 2005, pp.20–21).

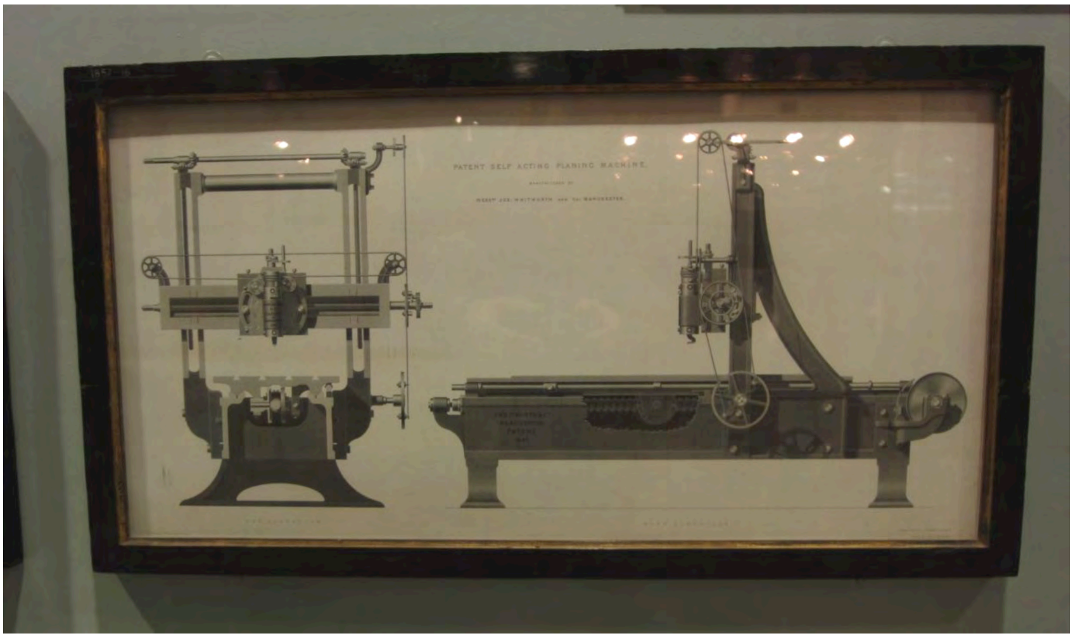


Fig. 7 Drawing of Whitworth's 1840 patent for a Self Acting Planing Machine, Science Museum, London. Photo: T. Jørgensen, 2011.

Additive Manufacturing (AM) methods include most of what is known as Rapid Prototyping (RP) and 3D printing. Although still relying on a basic CNC principle, AM (unlike CNC milling and cutting) is based on a principle of creating a physical model of three-dimensional CAD drawings by building up objects layer-by-layer. AM was developed much later than CNC cutting, with the first patents being taken out by Housholder (1981), Hull (1986) and Deckard (1989). The first commercial AM machine supplier, 3D System, was established in 1986 (3D Systems, Inc., 2011).

This project, with its focus on RPT, can best be located in the 'formative' category, which, of the three sub groups, is the least developed and studied. Formative digital fabrication techniques are characterised by computer driven machine tools that, through the application of force, shapes material into the desired form. Formative techniques include Incremental Sheet Forming, which is based on the same principle as metal spinning, where metal sheets are stretched into the desired shape. CNC wire bending, and the larger scale version of this technique, profile bending, also belongs to the formative category of CNC manufacturing (Callicott, 2001, p.38).

The concept of digitally enabled RPT has also been described under the general heading of Rapid Tooling (RT). Although still in general use, this term, along with

Rapid Prototyping (RP), and the even broader definition of Rapid Manufacturing (RM) (Hopkinson et al., 2006), could all be seen as somewhat ambiguous. Common for all these terms is that they are now generally used to describe methods of prototyping and manufacturing that are digitally driven.

5.3.2 Reconfigurable Pin Tooling

The concept of Reconfigurable Pin Tooling (RPT) provides the specific technical focus for this research. The first part of this section will focus on research and practice concerning RPT in the field of engineering, while the latter part will outline work by creative practitioners with the concept.

The concept of RPT is based on a principle which could best be described as a *bed of nails*. It is a concept that is also known from a popular 1980's toy sold under brand names such as 'PinArt or PinPression', the invention of which is credited to the American artist, Ward Flemming (Fleming, 1985). However, the principle of using an array of pins to represent three-dimensional forms has been explored by inventors and researchers as a flexible tooling method for at least 150 years. The concept has been at the centre of the search for an ultimate tooling or moulding method, where a single apparatus can be reset to produce an infinite variety of shapes, such a tool has been described as an 'universal' or 'ideal' tool (Munro and Walczyk 2007). Despite the attractive properties of such tool, the technical challenges associated with the construction and operation have meant that only a few operational systems have been constructed with very limited commercial application (Munro and Walczyk 2007, pp.551–552).

At least 38 patents have been filed relating to RPT techniques (Munro and Walczyk 2007), with the first by Cochrane (1863) concerning a method for fabricating leaf springs. Several other patents were filed in the period until the mid-twentieth century, but it was the advent of NC and CNC that lead to a significant increase in the interest of the concept, with the first patent relating to a CNC driven RPT system by Pinson (1980). Monro and Walczyk (2007) highlights that more than half of the patents relating to RPT have been filed after 1990 and makes a clear link with the advances in the use of CNC technologies and increased research into RPT.

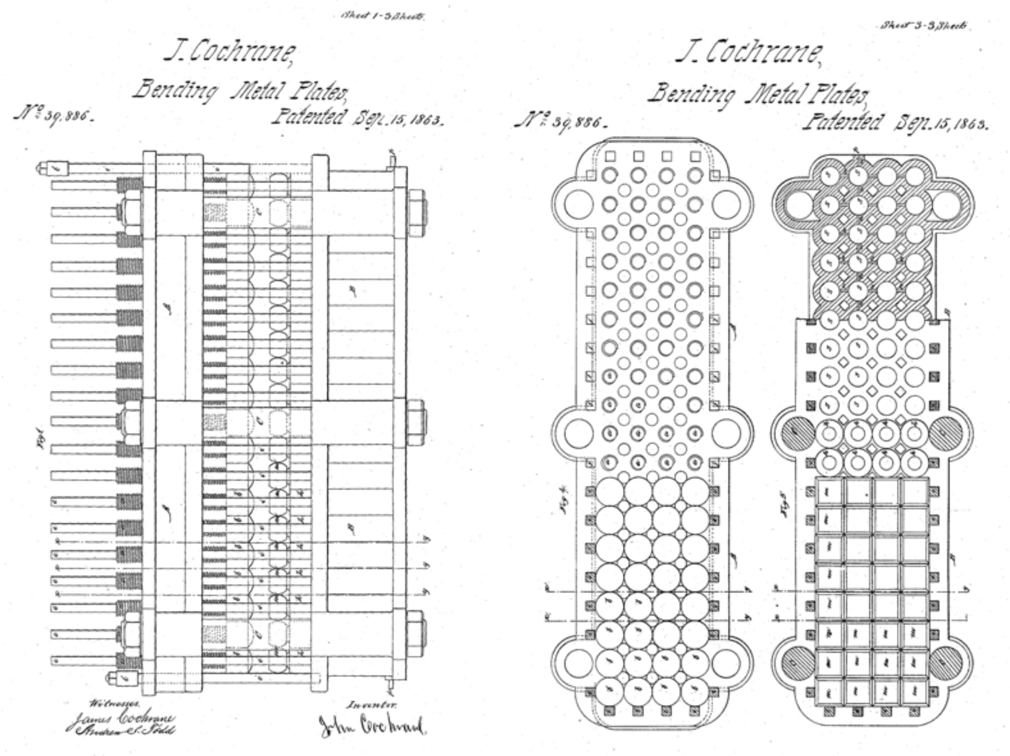


Fig. 8 Diagrams from Cochrane’s patent (1863)

The challenges of developing a functional RPT system are rooted in conflicting demands of various aspects of the concept. These include pin actuation, robustness, surface quality, locking mechanism, tool weight, cost, and the ease and speed of use. Given the nature of the concept, resolving one of these aspects may have a detrimental effect on another feature, and therein lies the greatest challenge in establishing a successful RPT system.

The RPT systems that have been developed rely on two basic types of pin arrays, one where the pins are uniformly spaced and one where they are positioned in a closely packed matrix (see Fig. 9) — an arrangement which has also been described as a 'discrete die' (Walczyk and Hardt 1999). Most researchers have used systems consisting of matrices made of equal squares, but other tiling patterns have also been proposed (Walczyk and Hardt 1998, p.438). The uniformly spaced approach generally present easier pin positioning, whereas the closed packed matrix provides a better structural support for applications which require a very durable moulding tool.

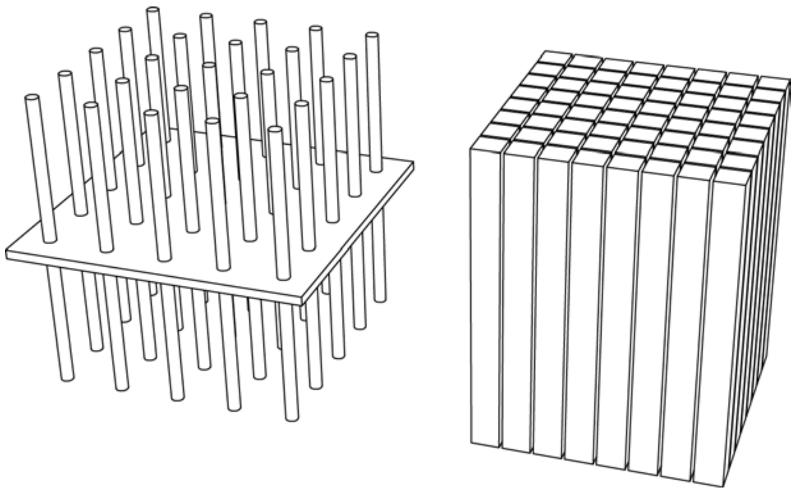


Fig. 9 Illustration of ‘equally spaced’ and ‘closely coupled’ RPT principles.

A number of approaches have been explored in terms of pin actuation with the most commonly used method being based on a lead screw actuation and fixing. The operation of such a lead screw can be done by a standard three axis CNC machine, turning each individual pin into position. However, this approach has been reported to be very slow (Walczyk 1996). To achieve a faster way of setting the pins, servomotors for each individual pin (or clusters of pins) have been explored. However, this approach increases the complexity of the controller system; an issue that is particularly evident with RPT systems that contain a high number of pins (Papazian, 2002). Apart from the lead screw approach, other actuation methods have also been proposed and developed. These include a system based on hydraulic actuation by Papazian (2002), and a vibrating, sweeping ‘push rod’ presented by Nakajima (1969).

A mould that is constructed by individual standardized elements, as is the case with RPT, will, for some shapes (especially when representing shapes consisting of compound curves) inevitably result in a dimpled surface. The impact of this inherent issue is to some degree dependent on the application of the RPT system and, in particular, the nature of the medium that is being moulded. However, as the majority of the research into RPT has focussed on sheet metal forming, the dimpling issue has been one of the major challenges in producing a successful RPT system. The most common approach to resolve this has been to use a soft, flexible membrane to create an interpolated mould face on top of the pins, but other approaches to smooth the surface of the RPT mould have also been proposed and developed. In this regard, swivelling pin tips have been explored by several researchers (Wang 2009; Weinstein 2012; Knight 2000). Another potential solution is presented by Papazian et al. (2001), with pin heads that are capable of changing shape.

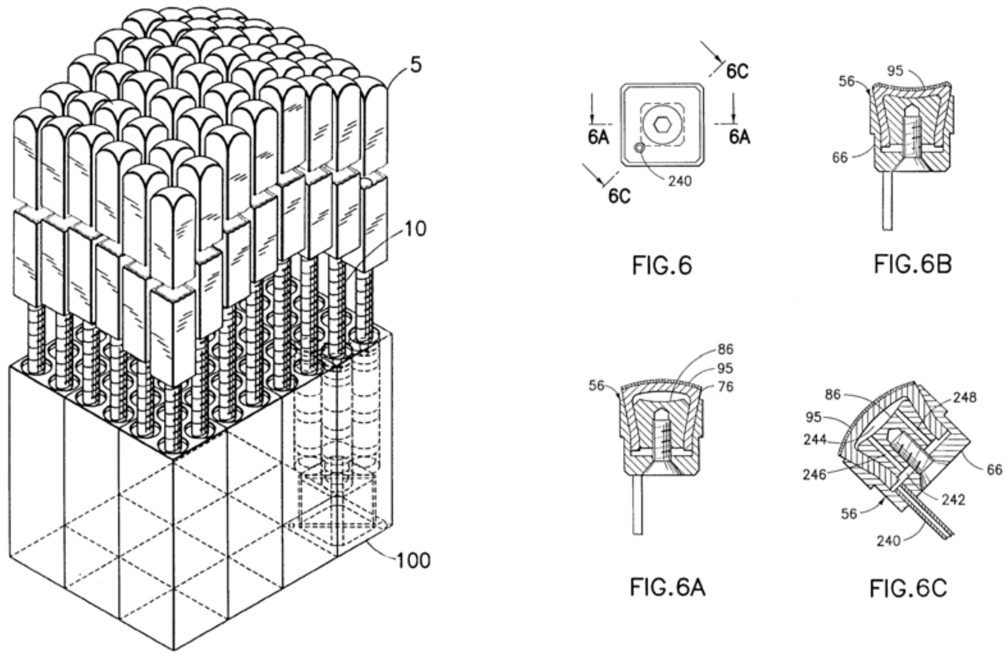


Fig. 10 Diagrams from by RPT patent by Papazian et al. (2001)

The issue concerning surface resolution has also been resolved by a subsequent milling processes to achieve a completely smooth mould face. The UK firm Surface Generation have developed a hybrid system called Subtractive Pin Tooling (SPT), which employs this approach (Halford 2005; 2005b).

Overall, there have been very few examples of RPT being employed in practical or commercial applications. The efforts of applying RPT have predominantly been focused on relatively heavy engineering applications, particularly in sheet metal forming, which is a process that presents very demanding requirements on the moulding tool. A major investigation which explored this application was the 'Flexible Die System' at MIT, lead by David Hardt (Hardt et al. 1982). This project later developed into a lager project called 'Reconfigurable Tooling for Flexible Fabrication' (RTFF), which explored the practical application of the concept in the production of aircraft panels. The project was funded by the US Defence Advance Projects Agency and undertaken by a consortium consisting of MIT, Northrop Grumman Corporation and Cyril Bath Company (Walczyk et al. 1998; Munro and Walczyk 2007; Papazian 2002). This project resulted in one of the few existing commercial RPT systems, however, the researcher has been unable to find evidence confirming that the tool is currently in use. The system, which is used for stretch forming metal, is reported to have cost over $ 1 million and weighs twenty tons (Munro and Walczyk 2007).

Many proposed applications for RPT have involved vacuum forming and moulding of some kind, with a number of patents having been filed for this application (Meilunas et al., 2002; Wang, 2009). Wang (2009) carried out extensive testing on this application, using a reconfigurable mould system constructed by interlocking threaded pins based on a principle first patented by Berteau (1994). Other moulding applications using composite materials with the RPT concept have also been explored (Munro 2006; Owodunni et al. 2004). Equally, Surface Generation's SPT system is reported to have been used in the marine industry and with various other moulding applications (Halford 2005). The sail manufacturer North Sails is currently employing a reconfigurable moulding system for the fabrication of its 3DL sails. Although the system is based on actuators rather than pins, it remains very similar to the RPT principle (North Sails Group LLC 2011). A number of researchers have also been investigating RPT as a method of clamping irregular shaped parts during machining processes (Al-Habaibeh et al., 2003; Moore and Gindy, 2006), however the researcher has been unable to identify examples of this application in commercial use.

The findings of this review concludes that despite the considerable amount of research that has been carried out on the RPT concept, researchers appear to agree that a genuine successful RPT system for manufacturing has not yet been achieved. (Owodunni et al. 2004; Munro and Walczyk 2007).

In addition to Fleming (1985), a number of artists, designers and inventors from outside the field of engineering have also explored the reconfigurable pin concept, with arguably more successful results. The Russian artist Alexandre Alexeïeff developed an animation method based on the pin-screen principle during the 1930's, and employed the technique to create a series of short films with unique visual qualities (Lopes 1999; McLaren 1974).

Contemporary designers Andy Brayman (The Matter Factory, 2011) and Julian Bond (Bond, 2011) have both explored the RPT concept with ceramic designs.
Nikolas Weinstein Studios (Weinstein, 2012) has developed an RPT system for kiln forming clusters of glass tubes to create large scale art installations. The system

has been successfully employed by the studio in the construction of several installations over the last 10 years (Knight 2000; Weinstein 2012). The researcher has also carried out his own explorations of RPT to successfully develop a system to create glass artefacts (Jorgensen, 2010a, 2010b).

Several researchers have also used the reconfigurable pin concept in the field of interaction design. These include an exploration of combining computer graphics with a haptic interface as demonstrated by Iwata et al. (2001). Zhu developed a prototype of a system for a haptic display in the Digital Clay project (2005), and a low cost version of an actuated display is presented by Leithinger and Ishii (2010).

5.3.3 Survey of Self-Build Digital Fabrication Projects

A survey of projects concerning individual innovators' work with digital fabrication was carried out in 2011 at the outset of this study. The survey was intended to provide key indicative examples of the developments in this field, providing a key contemporary context for undertaking the practical elements of this research. The criterion for this search was to identify projects by individuals innovating with digital fabrication processes rather than projects which just make use of commercially available technologies. The review focuses on projects that have been created by individual innovators but also includes projects that have key relevance to this particular group.

As the oldest and most established of the digital fabrication techniques CNC machining has been the focus of many self-builders' projects, with examples of highly capable CNC milling and routing machines being developed. Such projects include, Ross Anderson's Junkbot (2008), and Rab Gorden's very impressive range of CNC machines, which include a five axis gantry router. Gorden is also the creator of the open source, CNC Toolkit, which is used by individual practitioners as an alternative to an expensive commercial five axis milling software (Gorden, 2011).

Fig. 11 Five axis router (2006) created by Rab Gordon, photo: R Gordon, 2006 (image reproduced by kind permission of R. Gordon).

A key enabling element of the development of self-building approach with CNC machining can be linked to an initiative by the National Institute of Standards and Technology (NIST) in the US in the early 1990's (Shakelford and Proctor, 2000). This initiative focused on establishing an open architecture controller for machine tools. The work culminated in the creation of Enhanced Machine Controller (EMC) software. The software was released as an early open source project running on Linux (Shakelford and Proctor, 2000). However, the software suffered from low stability and it was not until the programmer, Art Fenerty, developed the software into the 'MACH' CNC control software that the full potential of this work was reached (Mauch, 2005). The commercial (but low cost) MACH3 CNC control software has now over 20,000 users and is recognised as one of the key facilitating tools in enabling the development of self-build CNC projects (Mauch, 2005).

Since the early 2000s a small-scale industry has developed which supplies CNC components or machines in kit forms, examples of such companies include: DIYCNC (Xtreme Precision Engineering Ltd, 2011), Geckodrives (Geckodrive Motor Controls, 2011) and Routout CNC (Routout CNC Ltd, 2011). A number of companies also supply blue print plans for CNC machines, thereby providing self-builders with an easy entry level for creating their own machines. ShopBot Tools Inc. was one of the early suppliers of CNC kits, and the company has now grown to be one of the biggest manufacturers of affordable CNC routers aimed at individual makers and small companies. Ted Hall, Shopbot's founder, started the company after constructing his own CNC router to use with his hobby of building plywood boats. Hall recognised a growing market in supplying affordable CNC equipment, and since being established in 1996, Shopbot Tools has now shipped almost 6000 CNC routers (ShopBot, 2011).

Other CNC based fabrication methods, such as laser cutting, have now also been the subject of self-build projects. Addie Wagenknecht and Stefan Hechenberger from NortD Design Labs have, since 2010, been documenting their ongoing Lasersaur project of developing an open source laser cutter. The project has now entered the final beta phase, and the knowledge generated is due to be released shortly under a GPL licence (Hechenberger and Wagenknecht, 2011).

Although strictly speaking not a fabrication method as such, the Hector project from 2002 provides a very good example of individual practitioners developing a system with an entirely novel approach. The project was a collaboration between Jürg Lehni and Uli Franke in an attempt to challenge what they considered to be a growing 'monoculture' in the output from graphic digital design tools. Their aim was to develop a method of expressing computer graphics in a much more physical and expressive way. The CNC graffiti painting system they created was highly innovative, based on a novel approach with a spray can being suspended on two cables articulated by CNC stepper motors. The whole system was built from scratch, including custom etched PCB boards. The team also wrote customised software to enable their system to interface with commercial graphic software and extended this interface with additional scripted algorithms to ensure a smooth operation of the suspended spray can (Franke and Lehni, 2002).

Examples of such novel approaches also exist with more genuine fabrication projects. The Formtexx company, established by John Gould and Linda Barron in 2008, is commercialising inventions which Gould has been developing since 2004. The system they have established is a digitally controlled manufacturing method capable of shaping metal sheets into double curved panelling. The technology is based on a robotic hammer that is operated via specialist software. Since launching in 2009 the project has received a very high level of interest, especially from the architectural sector (Armadei, 2009).

Gregory Epps' work with robots also presents a very interesting approach. Epps has developed a system which is based on paper origami techniques but applied to metal sheets, which, through coordinated simultaneous manipulation of several robots, can created curved and creased panels for the architectural sector (Epps, 2011).

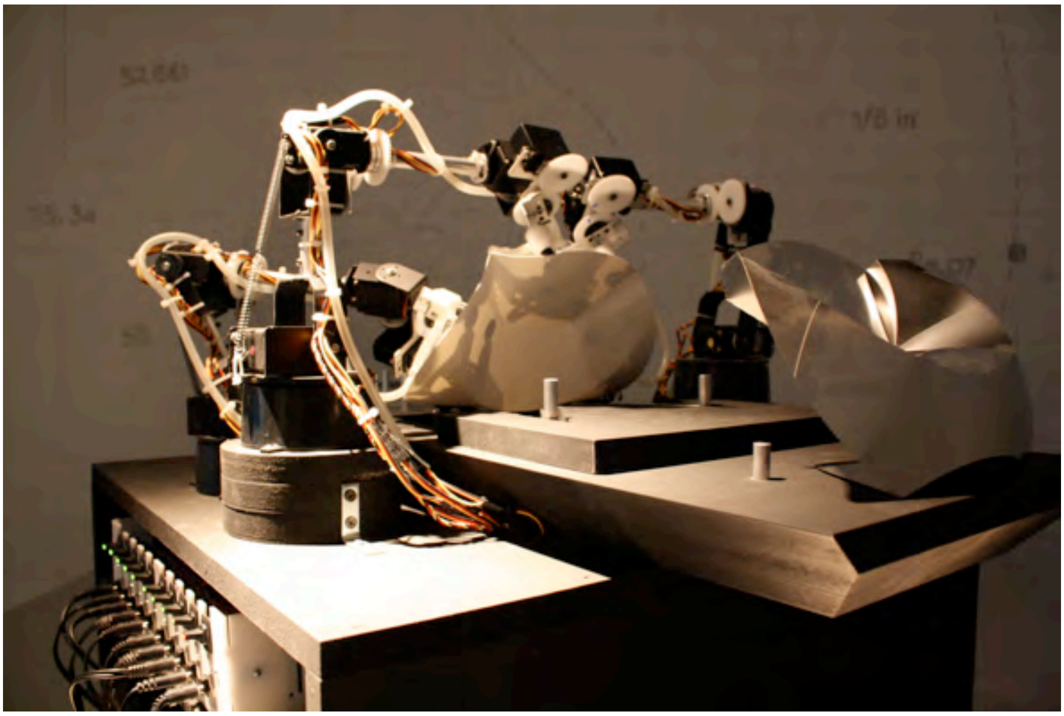


Fig. 12 Gregory Epps' Robofold system, photo: Ema Epps, 2009 (image reproduced by kind permission of G. Epps).

Arguably one of the most influential digital fabrication projects in recent years has been the RepRap project. The project was started in 2004, and conceived and lead by Dr Adrian Bowyer from the Department of Mechanical Engineering, University of Bath (Jones et al., 2011).

The initial intention for this project was not aimed at contributing to the field of digital manufacturing, but rather to explore the concept of self-reproduction (Jones et al., 2011). Building on John von Neumann's work on the concept of a kinematic self-reproducing machine, the team at the University of Bath developed a Rapid Prototyping (RP) machine which is capable of producing a significant proportion of the components needed to make a copy of itself (Jones et al., 2011).

The technical principle for the RepRap is very similar to commercial Fused Deposition Modelling (FDM) RP machines that are produced by Stratasys (Stratasys Inc, 2012a). Crucially, the RepRap project, with its intention to create a self-replicating system, made all plans and software freely available under an open source GPL license (Bowyer, 2011). Furthermore, the design of the RepRap is such that the remaining parts which the machine cannot replicate are constructed from cheap and widely available parts. The concept enables anyone to build their own RepRap Machine at the cost of €300 to €500. The consumable material, usually ABS or PLA plastic filament, is also readily available at low cost. As users build and replicate the machines they will inevitably discover aspects of the construction which can be improved and make their own adaptations. By releasing the *know how* of the project under a GPL license these improvements are required to be freely disclosed back to the 'commons' community so other users can benefit from these improvements. The effect of this approach is that the next generations of RepRaps will improve and become better machines, and through the law of evolution (which was part of the initial research aim of the project) find their natural position in the ecology of digital manufacturing.

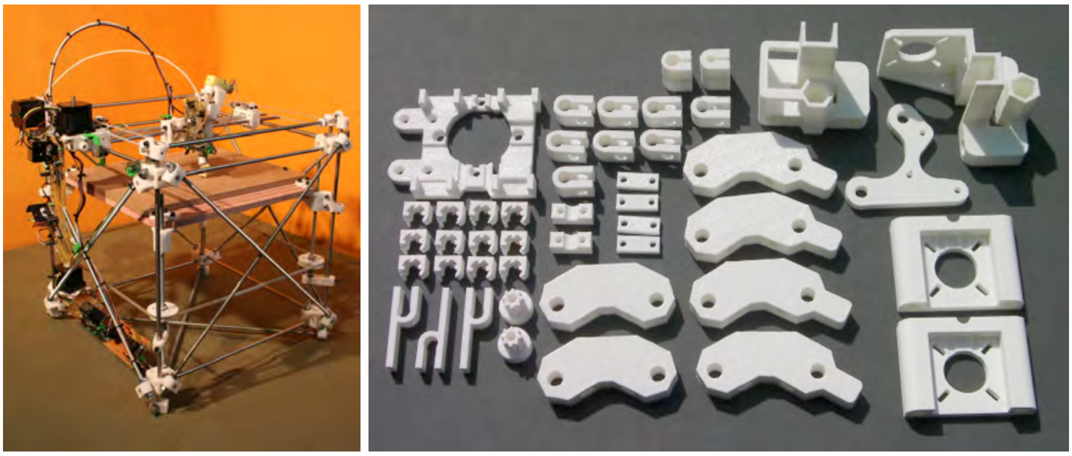


Fig. 13 The RepRap machine and self-replicating parts (images reproduced under GNU Free Documentation License 1.2.)

To date, the RepRap project has been extraordinary successful. One of the outcomes has been the emergence of a number of derivative designs known as 'RepStraps'. These are commercial versions of the RepRap, sold either as kits for self-assembly or completed machines. There are now numerous companies that are selling their own versions of RepStraps including: Bits from Bytes, Bootmill, Ultimaker and Makerbot Industries. The RepRap project has also inspired other research into low cost RP systems such as The Fab@home project by Cornell University. The Fab@home employs a different construction and can use a wide range of different materials.

The proliferation of RepRaps and RepStraps has be extraordinarily rapid, Jones et al. (2011, p.190) reports that only four RepRaps were in existence in 2008 and estimates that by mid 2010 there were approximately 4500 machines worldwide. Makerbots Industries claimed, in August 2011, to have sold 5200 units since commencing production in mid 2009 (Pettis, 2011). In comparison, Stratasys, who is the current market leader in terms of commercial (and non open source) RP machines shipped 600 machines in the third quarter of 2011 (Stratasys, 2011).

While the current crop of RepStraps is still largely targeted at the hobbyist sector, there are signs that investors are taking increasing notice of these developments. An example is the Foundry Group's announcement of a $10m investment in Makerbot Industries (Foundry Group, 2011; Pettis, 2011). This follows 3D System's (which is the world's current largest commercial RP company), acquisition of Bits from Bytes in September 2010 (Johns, 2011).

Individual design practitioners are now starting to explore ways of extending the capability of the RepRap to include new materials and applications. Tim Knapen in collaboration with the Belgian design studio, Unfold, adapted a RepRap to print with ceramic slip rather that plastic filament. They integrated the machine within a complete virtual pottery wheel creative system, which included a custom created interface based on laser beams recording forms defined by hand gestures (Unfold, 2010).

The build envelope of most RepRaps and RepStaps is still fairly limited, typically a 20cm square cube, but other projects are working on a much larger scale. Enrico Dini, working in Pisa, Italy, has single-handedly developed the 'D-Shape' system (Monolite UK Ltd, n.d.), which, just like the RepRap, work on an AM principle. But rather than employing an FDM AM concept, this system uses a powder based approach — a concept which is also employed in the plaster powder based 3D printers supplied by the commercial company ZCorporation (Zcorperation Inc., 2011). Dino's D-Shape system is based on spreading layers of sand, with each layer being sprayed with a magnesium based solution to create free-form structures on an architectural scale. The system has not yet reached a stage of commercial application, but the project has received significant interest from the architectural sector, with some funding being supplied by Foster and Partners.

Fig. 14 The ‘D-Shape’ system by Enrico Dini, photo: D Shape 2009 (image reproduced by kind permission of E. Dini).

Also working with sand as the build medium is the Royal College of Art graduate, Markus Kayser, who has created an experimental fabricator called *The Solarsinter* (2011) This system employs a Fresnel lens to focus solar rays to melt layers of sand into crude forms. The principle is similar to that used in commercial Selected Laser Sintering (SLS) technology. The machine was successfully tested in the Egyptian dessert in 2011, powered entirely by solar rays.

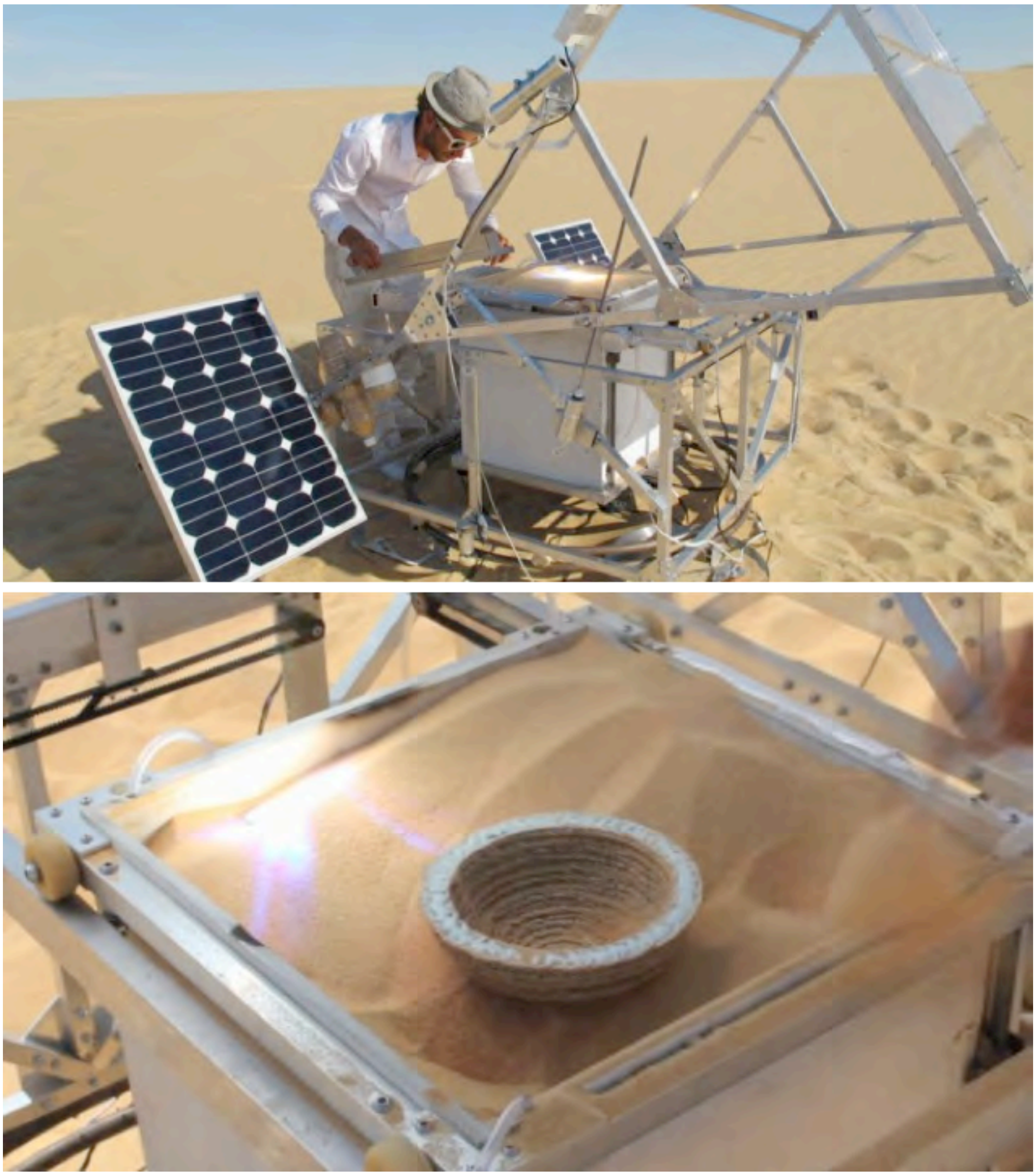


Fig. 15 Markus Kayser's *Solarsinter* project (Kayser, 2011), photo: Amos Field Reid 2011 (image reproduced by kind permission of M. Kayser).

While most of the systems based on the RepRap template generally suffer from low surface quality, projects have been undertaken to try to emulate other, more sophisticated, AM technologies. These include SLS, Stereolithography (SLA) and the newer Digital Light Processing (DLP) process, which can achieve a very high surface quality. Both SLA and DLP use light sensitive resins as the build medium. Junior Veloso (rumoured to be based in Singapore) has posted details of a DIY project developing a DPL system which indicate a very high quality surface finish on the build parts (Veloso, 2010). Other DPL projects are also underway and a community of DIY builders exploring this technology has been established on Yahoo (DIY 3D Printing and Fabrication, 2011). A slightly crude, but still successful, attempt at SLA has been posted on the *Instructables* website (Hopeless, 2011). These and other projects provide increasing evidence that even the most sophisticated AM technologies are now being targeted by self-builders.

There is evidence of many more experimental fabrication approaches being explored in universities and colleges. The (FAB)BOTS (IAAC, 2011) project illustrate such explorations. The project was undertaken in 2009-10 as a collaboration between the Architectural Association in London and the Institute for Advanced Architecture of Catalonia, Barcelona. Teams of students worked for periods of up to 12 months to develop operational prototypes for experimental and highly novel fabrication systems. The aim of the project was 'to investigate the work flow between computational design and material production methods, through the invention and development of customised numerically controlled fabrication devices and innovative material solutions' (Malé-Alemany, 2010, p.3). The systems developed include: *Fibr(h)ous(e)* — a concept for constructing housing using digitally controlled filament winding machine; *PNEUmorphosys* — a pneumatic driven apparatus for flexible formwork; and *Mimicry* — a system of self-organised robots capable of carving foam panels using eroding chemicals (IAAC, 2011; Malé-Alemany, 2010).

Many of the DIY and homebrew projects, which have been described in this review take inspiration from established commercial technologies, or are simply just direct copies of such systems. Essentially, this approach is a way for individual practitioners to create their own versions of commercial systems at a much lower cost.
However, the review also presents plenty of examples truly original digital fabrication approaches that have been developed by individual innovators and which have no relationship with existing commercial equipment.

This selection of examples are only a small proportion of projects in the field of self-build digital fabrication. Searchers undertaken by the researcher indicated that that overall experimentation and innovation in this field is vibrant and growing. Sponsorship and investment from established commercial companies illustrate that this approach to innovation is taken very seriously by investors. The potential for real economic impact creates an added relevance for undertaking this research.

While self-build innovation in both reductive CNC and ALM machines could be seen as a little tangential to this particular study, which is focused on a different manufacturing principle (that of formative manufacturing). However, apart from illustrating an overall increased activity in this field, these tools also presents individual practitioners with the power to create both cheap and sophisticated prototype parts for *other* innovation projects in the field digital fabrication, such as the exploration of RPT, which is the focus of this research.

5.4 Economic and Business Context

This PhD study was partly funded by the European Social Fund as a part of an initiative to support and increase growth in the Cornish Economy. This funding provides an incentive and rationale to review the wider economic and business context for this study. Relevant subjects included in this contextual section are: The Digital Economy, Flexible Specialisation and local economic conditions. The latter section includes a description of the Cornish business partner that collaborated with the researcher on this investigation.

5.4.1 Digital Economy

The emerging Digital Economy provides the wider economic context for this project. This broad context is perhaps commonly understood to impact most directly on sectors such as media and communication, however, reports by McCormick (2011) for the 'UK Knowledge Transfer Network', and Pescovitz (2008) for the 'Institute of the Future' highlights the specific relevance of the design and fabrication sectors in the broad context of the Digital Economy.

Negroponte is generally credited with defining the initial notion of the Digital Economy in *Being Digital* (1996). However, the specific term appears not to be used in the book, instead Negroponte describes the concept as the 'Information Economy' or the 'Digital Marketplace' (Negroponte, 1996, pp.11, 85). In the context of a fast developing digital technology sector, *Being Digital* has now to be considered a relatively old text. While the book is clearly focused on the field of media and communication (which at the time of publication had yet to experience the full impact of the digital technologies), many of the key concepts in the book could be seen as particularly relevant to the developments that are underway in the field of design and fabrication — developments that appear to follow a similar path to that of media and communication.

The central idea of *Being Digital* is the move from an economy which is focused on the exchange of services and products which take a physical form to one where products and services are exchanged (wherever possible) in a digital form — or as Negroponte puts it, a move from 'atoms to bytes' (1996). The notions of the Digital Economy could be seen as a natural progression of ideas concerning a post-industrial economy. Daniel Bell (1976) is widely credited with having coined the phrase as a concept to describe a move from a manufacturing based economy to one that is predominately based on the production and exchange of knowledge. While recognising this heritage, Negroponte argues that while a move to an information economy has long been underway, information and knowledge (at the time of writing) is still produced and exchanged in physical forms, such as books, CDs, newspapers, film and video (Negroponte, 1996).

Negroponte provides a number of surprisingly accurate predictions of the development of various digital technologies; in particular, a prediction of the impact of the Internet, which corresponds well to actual developments to date. Negroponte does not touch on the potential of digital manufacturing — in contrast, he argues that industries with outputs that cannot be rendered in a digital form are likely to see relatively little impact from the digital economy on their core business models (1996, pp.12,13).

However, a number of recent projects and the emergence of a number of new companies contradict Negroponte’s statement. These projects are concerned with the capacity of digital fabrication techniques to produce individually tailored products, a concept known as mass-customisation. The involvement of end-users or consumers as a co-creator in the design process are one of the key elements in these projects. Notable examples of companies that have explored this territory include Austrian based Fluid Forms (Fluid Forms, 2011). The company’s business model is centred on a website ‘shop front’ featuring a collection of designs which have online tools that provide consumers with the opportunity to customise the designs using personal data such as fingerprints, or by selecting sections of maps with personal significance as the basis for the design aesthetic. Following the customisation process (and payment) the designs are created via digital fabrication technologies such as CNC milling.

Nervous Systems (Nervous System, inc., 2011) use a very similar business model, but focus their designs on generative algorithms that simulate growth patterns in nature. Just like Fluid Forms, Nervous Systems offer consumer interaction via online tools, but extend the interaction with users by making some of their design source code available under a Creative Commons licence for others to explore.

The concept of web based tools as the basis for involving end-users as co-creators in the design process has long been advocated by Atkinson who has instigated several projects that have explored this territory — a notion which he describes as: 'Post Industrial Manufacturing Systems' (Atkinson et al., 2009). These projects, include Automake by Justin Marshall (Marshall et al. 2007) and Future Factories by Lionel Dean (Atkinson et al. 2008), although these projects have not yet reached full commercial application.

Several commercial companies are currently exploring similar approaches, including Ponoko (Ponoko Limited, 2011) and Shapeways (Shapeways Inc., 2011); both are web based digital fabrication bureaus that are extending their core service to include online design tools to enable user creation and interaction. The companies also host online market places for users to sell their own 3D designs. Ucodo, a proof of concept brand, was launched in 2010 by UK based Digital Forming Ltd, and they also explore a similar business model for User Co-Designed Objects (Digital Forming Ltd 2011).

While fabrication systems developed during this study are not focussed specifically on application in co-design or mass customisation systems, the reconfigurable nature of the RPT makes this research very relevant for such applications.

5.4.2 Flexible Specialisation

Apart from the potential relevance of mass-customisation, this research has equal potential in the context of manufactures with set-ups based on highly flexible production as the proposed RPT systems have the potential to enable prototyping as well as full-scale production from the same tooling apparatus. Such design and production concepts relate to ideas voiced by several authors who proposed digital fabrication as the basis for new business models, moving from mass-production to flexible, distributed or even personal production models (Gershenfeld, 2005; van

Abel et al., 2011). However, in this debate it is relevant to question whether such a clear dichotomy between production systems genuinely exists. Several authors report on the decline of the classic mass production models as early as the 1970s, with these models being replaced by other and more flexible production models (Piore and Sabel, 1984). These ideas are generally known as Post-Fordist theories and focused on the notion of 'flexible specialisation' (Amin 1994; Kumar 1995).

Kumar (1995) describes how this concept originates from observations of the business structures behind a high economic growth in the manufacturing sector in central and north eastern regions of Italy during the 1970s and 1980s — a phenomenon known as 'the third Italy'. Kumar describes how new small companies emerged in this region with typical 5-50 employees specializing in highly skilled niche production. These companies would often work together with other small companies in a collaborative way in order to supply a client with a complete service or product, thereby developing industrial districts of networked, interdependent subcontractors. These new companies generally employed workers with flexible and high-level skills often with production based on new manufacturing technologies; in particular, emerging NC and CNC machine tools. Kumar describes this set-up as 'high technology cottage industries' (Kumar, 1995, p.63). Central for the concept is the ability of a decentralised but yet interconnected business structure that is able to adapt quickly to satisfy a growing demand for more varied and customised products. This structure contrasts the far less flexible, centralized production models associated with the Fordist mass-production approach. The idea of flexible specialisation is further championed by Piore and Sabel (1984), proposing the concept as a return to more autonomous production models associated with craft practice. Some authors, such as Elam (1994), have questioned the validity of these theories, arguing that even in periods of the most intensive mass production a network of smaller and flexible companies have always existed to subcontract and service the needs of the larger mass-producing companies

A current debate in terms of production models appear to have been rekindled as a result of the developments in digital fabrication and it could be argued that the increase access to digital fabrication tools could herald a period of where the idea of flexible specialization could have renewed relevance.

5.4.3 Crowdfunding

As previously reported, open source projects (such as several Repstrap producers) are now starting to attract significant interest and funding from venture capitalists. However, another significant development in terms of enabling business opportunities for home-brew digital fabrication entrepreneurs is the emergence of web-based community funding, also known as ‘crowdfunding’. This research project is not funded via a crowdfunding model, but there are strong indications that this model is being increasingly used as a way of facilitating independent innovation in digital fabrication and the concept is therefore included as a part of the overall context of this research.

Crowdfunding is closely related to the notion of ‘crowdsourcing’, a term first coined by Howe (2006). The concept is based on the notion of using online networks to draw on knowledge and expertise from an undefined group of volunteers via an open call. The crowdsourcing and open source concepts could be seen as very similar as they both rely on the contributions from a community of volunteers with a shared interest, however, there are some distinctive differences. Firstly, crowdsourcing (unlike open source) can also involve an element of payment to the contributors. Furthermore, the combined knowledge of a crowdsourcing projects is not necessarily under the control or openly available to the community of contributors, but instead can end up as confidential commercial IP. Howe (2006; 2008) presents examples of large companies such as Proctor and Gamble, which have successfully adopted this method to extend their own in-house R&D efforts.

In practical terms, crowdfunding uses a method where individual entrepreneurs, designers or artists use online networks to seek seed founding from an open call to enable the development of particular projects. *Kickstarter* (Kickstarter, Inc., 2011) and *IndieGoGo* (Indiegogo, Inc., 2011) are examples of current leading crowdfunding sites. Notable home-brew digital fabrication projects, such as the Lasersaur project and Printrbot (Drumm, 2011) were both enabled through funding via Kickstarter. Printrbot (a Repstrap design) secured the second highest funding amount ($830,827) ever achieved on *Kickstarter*.

Such examples could be seen as indications that crowdfunding is likely to play an increasingly important role as a source of funds to enable individuals to innovate in the field of digital fabrication.

5.4.4 Local Economic Context and Industry Partner

Due to its low GDP the Cornish region has, for a number of years, been in receipt of European funding to improve economic performance. As previously mentioned, this study is funded by the European Social Fund as a part of these efforts. This section will provide the local economic context for this research, and a description of the main Cornish industry partner. The Cornish region has a high percentage of small companies, with 89.2% of all Cornish business employing ten people or less. Manufacturing remains a significant part of the region's economy, being the fourth-largest sector both in terms of employment (9.4%) and also in terms of Gross Value Added (9.6%) (Convergence Partnership Office for Cornwall & the Isles of Scilly, 2011). This project's focus on self-build innovation in the field of digital fabrication should be of particular relevance to the typical size of manufacturing businesses in this region.

The main industry partner in this project was the small furniture design company MARK Product, Penryn, Cornwall (MARK Product, 2012). The company was established as a partnership by Anna Hart and John Miller in 2008, and they sell a collection of furniture and lighting products designed by a number of well-known designers. The company does not manufacture its own products, instead relying on local subcontractors to produce its designs. The company's strap line is: 'Product of Cornwall', and the use of local manufacturing is further highlighted in the company's promotional literature with each piece of furniture carrying a factsheet that declares what percentage of manufacturing has been done in Cornwall, UK, or 'other'.

With MARK's business model of relying on small, flexible and predominately local subcontractors there are clear echoes with the structure of Post-Fordist manufacturing in 'the third Italy' of the 1970's. This project presents an opportunity to explore the increased access to tools for developing and applying innovative, digitally driven production approaches in a rekindled scenario of flexible specialisation.

5.5 Update of Contextual Review

The main contextual review was carried out in 2011 to provide the overall foundation for this study and to lay a foundation for the practice elements. Throughout this study the researcher has engaged in on-going observations and review of the contextual developments. As highlighted in the introduction to this section, some contextual aspects have undergone very rapid development during the course of this study. To enable this thesis to be presented and analysed, and in relation to a current contextual situation, an update is provided to report on some key sector developments. Equally, the update also reflects on contextual developments that have taken place in terms of the RPT concept. Also included in this update are reflections on S-curve theories. During the study the researcher developed an interest in this theoretical framework. These theories helped to provide a lens for critical reflections on the practical aspects of this research.

Surprisingly, during the time that has elapsed since the initial contextual review the RPT concept appears to have received relatively limited attention from other researchers and innovators. However, some projects do warrant inclusion in this update. These include an RPT project that was carried out at the University of Michigan (UMich) in 2011-2012, which focussed on forming sheet glass. The researcher undertook a trip to UMich in March 2012 to see the system first-hand. At the time, the researcher was already engaged in establishing his own glass RPT system as a part of the practice element of this study, but it became apparent during the visit that the two systems were very different both in terms of construction and application. The UMich project was based on a collaboration between faculty staff members, Wes McGee and Catie Newell, resulting in the construction of a glass RPT system very similar to the one used by Weinstein Studios. The outcome of the project was the creation of an architectural installation consisting of hanging sheet glass elements (Newell, n.d.).

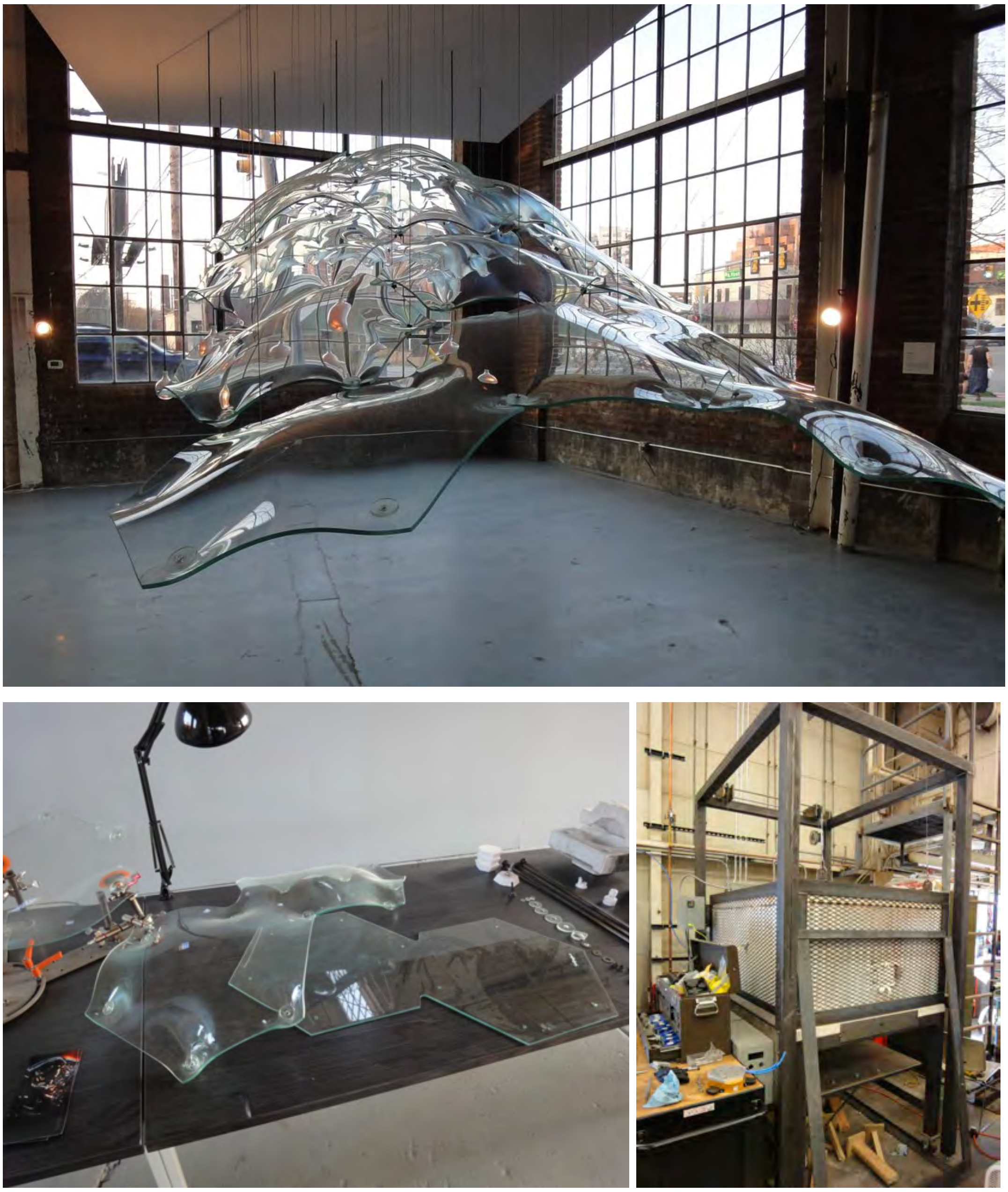


Fig. 16 Catie Newell and Wes McGee’s RPT glass project at the University of Michigan, Taubman College of Architecture and Urban Planning, photo: T. Jørgensen, 2013.

Another RPT project that warrants inclusion in this contextual update is architect Asif Kahn’s *MegaFaces* installation for the Sochi 2014 winter Olympics. This project featured a giant pin screen with 11000 illuminated actuated pins, which users could interact with by uploading their own three dimensional facial image on a giant pin screen (iart, 2014; Khan, 2014). While this project was intended to be an interactive exhibit with little emphasis on the manufacturing element, the underlying principle is almost identical to that of RPT. The scale and complexity of this installation is impressive and may inspire others to explore the pin screen or pin-tooling concept.

Fig. 17 Asif Kahn’s kinetic façade, *Megafaces* at the Sochi Winter Olympics 2014 photo: Nick Hufton 2014 (image reproduced by kind permission of A. Kahn)

Other relevant research in the field of interface and interaction design is the inFORM project from the Tangible Media Group at MIT’s Media Lab. This project, lead by Daniel Leithinger and Sean Follmer, established a highly sophisticated system with 900 actuated pins in a tangible user Interface (TUI). The system combines physical shape changing capabilities with co-ordinated projected digital content that enables a system with extended levels of user interaction termed 'physical affordances' (Follmer et al., 2013; Leithinger et al., 2014).

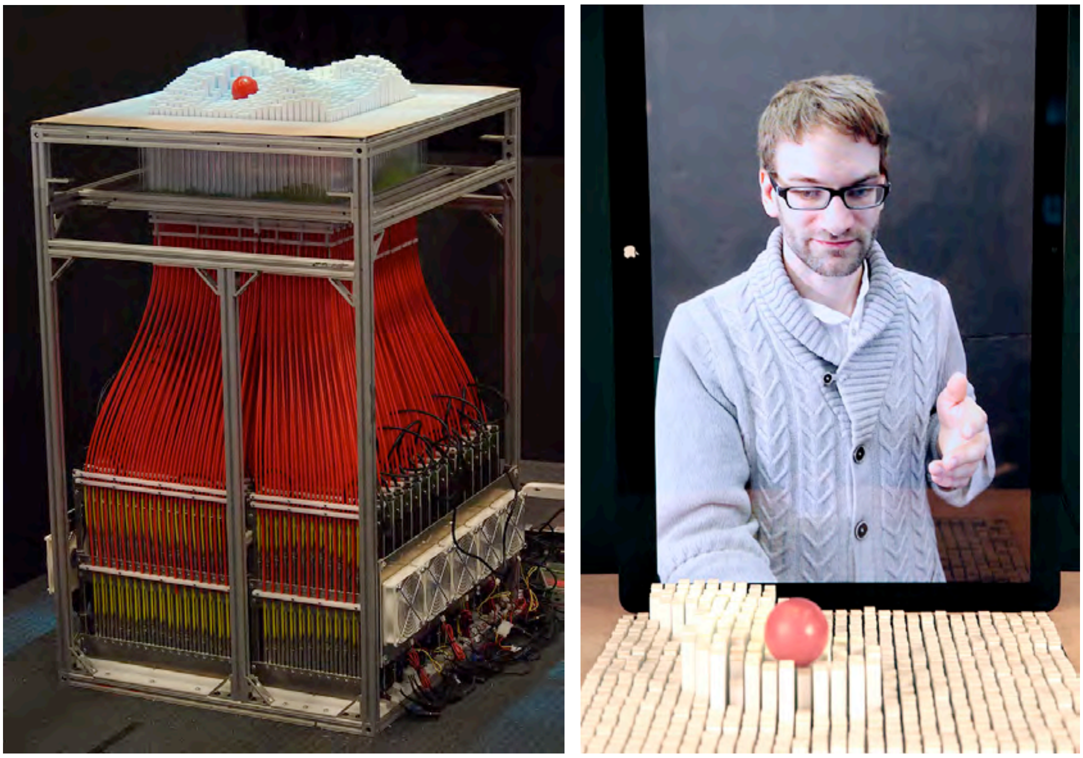


Fig. 18 The inFORM system develop by the Tangible Media Group at MIT, photo: © 2012 Tangible Media Group / MIT Media Lab. Licensed reproduction under CC BY-NC-ND 3.0.

In contrast to the relatively modest level of activities regarding RPT, the field of digital fabrication, with 3D printing in particular, has seen very significant developments since the initial contextual review was undertaken. From a concept that was relatively unknown to the general public at the beginning of the 2010s, 3D printing has, over the preceding years, received so much press coverage that the basic concept is now widely recognised by the general population.

The press coverage followed a rapid growth in the DIY and hobby sector of 3D printing, particularly driven by increased availability of a variety RepStraps. As a result, low cost FDM 3D printing systems are now commonplace today with systems also being sold by general consumer retailers such as Maplin (Maplin Electronics, 2014). While FDM systems are still the most widespread technology in the low cost sector, other ALM technologies such as DLP and SLA are also becoming increasing widespread.

Equally, many other experimental projects in the field of 3D printing have also fuelled the public interest in this sector (Aigner, 2012; Bertassoni et al., 2014; Defence Distributed, n.d.; Dovetailled Limited, 2014), and It would be impossible to cover all of the many developments and projects which have been spawned in digital fabrication over the last three to four years.

However, in order to establish a lens for reviewing the broader developments within this sector, the development of Makerbot Industries provides a useful case study, just as it did for the initial contextual review. This company, just like many other start-ups in this sector, was established on the basis of the increased diffusion of the knowledge in this sector, particularly the open source RepRap initiative that was previously described. Makerbot gained substantial success with a rapid growth in the sales of its RepStraps based products. A significant shift came in 2012 when the company announced a move from an entirely open source platform to a partially closed one (Pettis, 2012). A further development came in 2013 when the established ALM company Stratasys announced its acquisition of Makerbot Industries (Stratasys Ltd, 2013). Makerbot Industries' *journey* as a company could be seen as an indicative reflection of the developments in the ALM sector over the over the last five years.

As described in the initial contextual review, a plethora of start-up companies were established in the wake of the RepRap project and were also fuelled by other initiatives such as the FabLab project. While company start-up activity in this sector continues, there are also indications that the innovation environment in this sector is changing. In the early parts of this period (from the late 2000's) the innovation initiative appeared to be with independent actors in the field. In response, the established ALM companies, such as 3D Systems and Stratasys, undertook initiatives to protect their business interests from potential competition from the low cost system being offered by start-up companies. In this process, 3D System's undertook a number of business acquisitions, buying up a number of smaller start-up companies, such as Bits for Bytes (Bits for Bytes, 2010), Freedom of Creation (Freedom Of Creation, 2011) and The Sugar Lab (Park, 2013). Further consolidation was also undertaken though the acquisition of other established ALM competitors and related technology firms, such Z Corp Inc. (3D Systems, 2012) and Rapidform (TCT, 2012). As well as buying up companies, 3D Systems also sought to protect their business interests in a well publicised move to take legal action against the crowdfunding site *Kickstarter* and the SLA based 3D printer start-up company, FormLabs (Flaherty, 2012).

This strategy of business acquisitions and legal action is mirrored by the actions of Stratasys — the other main company in the ALM sector. As well as acquiring the high profile Makerbot Industries, Stratasys, just like 3D Systems, also joined forces with more established manufacturing industry focussed companies such as Objet (Stratasys Inc, 2012b). And just like 3D Systems, Stratasys have undertaken legal action against competitors in the consumer section of the 3D printing sector (Weinberg, 2013).

Based on these developments it would appear that Stratasys and 3D Systems are in the process of securing a position as two dominant companies in this sector. During this process they are adopting what Freeman and Soete describe as 'defensive innovation strategies' (1997, pp.272 – 276). Although innovation in this sector still appears diverse and vibrant, the developments just described could be seen as indications of a developing oligopoly.

5.5.1 Developing the Theoretical Framework on the basis of Contextual Developments

As previously highlighted, there has been significant development in the field of digital fabrication during the duration of this study, with ALM technology being at the core of these developments. In addition to the high level of general press coverage, commentators and scholars have also sought to study the growth in the sector. In this effort of analysis, 3D printing has frequently termed this as an 'disruptive technology' (Desjardins, 2014; McKinsey Global Institute, 2013).

The term ‘disruptive technology’ originates in innovation theory based on the concept of technology S-curves (Christensen, 1997). In the initial contextual review several innovation theories were outlined, however S-curve theories were not included in these discussions.

Through the on-going developments in digital fabrication the researcher’s interest in these theories increased with a growing realisation that a theoretical framework could be in developed in relation to the researchers' own investigation, based on these concepts. In the following section these theories are reviewed and discussed from a particular perspective in relation to the recent development in digital fabrication. Technology S-curve theory concerns the various rates of diffusion that a technological innovation undergoes during the uptake of the technology in a commercial or consumer context.

Gabriel Tarde (1903) is attributed to be the first to have presented the diffusion rate of an innovation as an S-curve graph. Rodgers (1962) expanded on this research and provided an underlying bell curve to illustrate how various groups of users that are involved in different stages of the technology uptake in an complete innovation sequence (see Fig. 19).

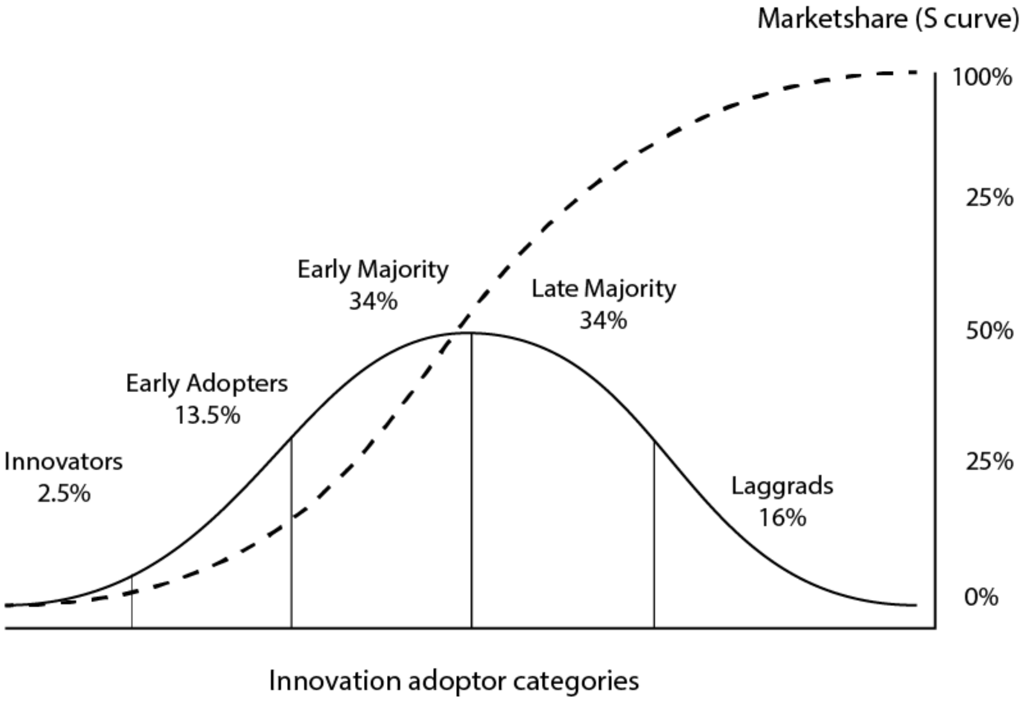


Fig. 19 Bell curve illustrating the various categories of users/consumers' uptake of a particular innovation. The line of dashes illustrates the cumulative market share in the shape of an S-curve. After Rogers (1962).

The use of the S-curve to illustrate the uptake of an innovation is also presented by Foster (1986), whose work is further expanded by Christensen (1997). Although both Rogers and Foster's S-curve theories are concerned with the diffusion of innovation they present different perspectives.

The S-curves presented by Foster and Christensen charts a technology's performance in relation to the engineering efforts (or time) that is needed to achieve an increase in the financial return or performance of an innovation. In this model the physical limit of a technology or innovation will ultimately be reached where no amount of time or engineering effort will improve performance (see Fig. 20).

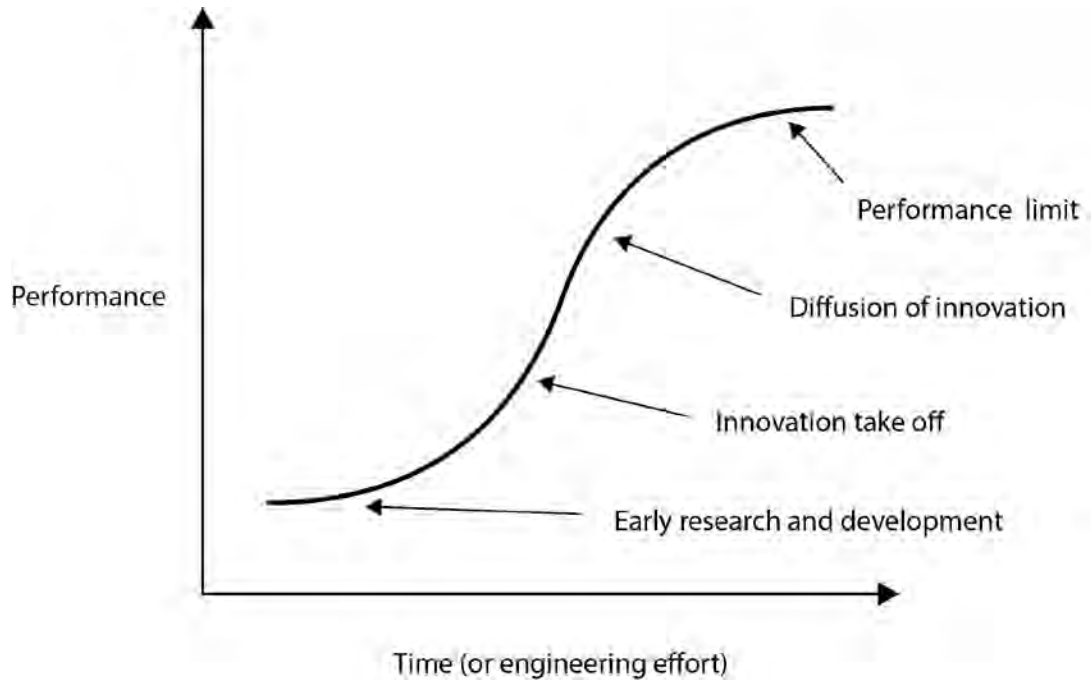


Fig. 20 Innovation (or technology) S-curve after Foster (1986) and Christensen (1997).

Forster (1986) provides several case studies which are discussed in relation to this model. These include both historical examples as well as more contemporary cases. The historical case studies chart the performance of sailing ships, pocket watches and cash registers. Foster discusses all these technologies in relation to the S-curve, showing how the *development* phase is initially slow with limited performance in relation to the time and engineering efforts employed. This phase is replaced by rapid improvement in performance during the *take-off* phase, which then in turn starts to level out when the innovation reaches a state of more widespread diffusion. Eventually, little or no performance gains can be achieved through engineering efforts as the technology reaches its physical limits for further improvement.

At this stage the particular innovation or technology is likely to carry the risk of being superseded by other technologies with a greater performance potential. Foster argues that such rival technologies are likely to already be underway in separate S-curve trajectories but positioned at earlier performance stages, such as 'development' of 'take-off'. As the rival innovation is not based on the same technology the S-curves are not joined, but, instead, a *discontinuity gap* separates them. Foster argues that technology S-curves almost always appear in pairs (or even multiples) as technologies that are engaged in battles to take over from an existing established innovation or technologies (see Fig. 21).

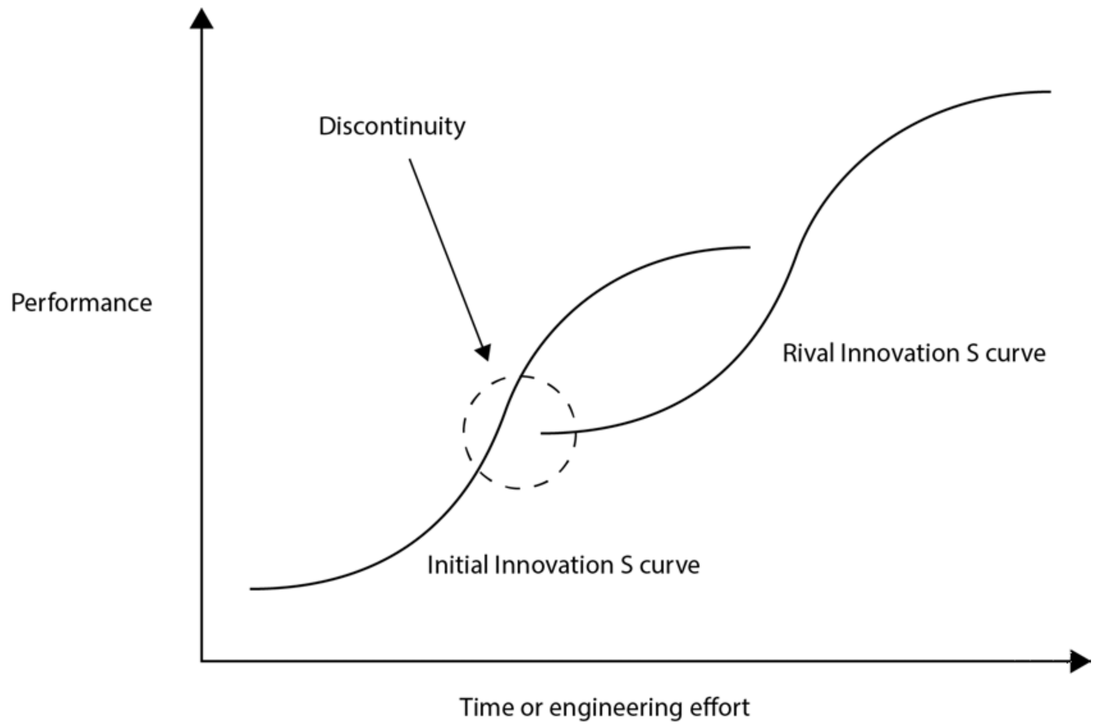


Fig. 21 A pair of innovation S-curves. The figure illustrates how rival technologies on a different S-curve stage can challenge and supersedes existing technologies that have already reached their performances limit. After Foster (1986).

To illustrate the rival S-curve scenario Foster (1986) provides the example of cash registers. In this example Foster describes how the National Cash Register (NCR) company during the early 1970s failed to recognise that their core product of electro mechanical cash registers had reached the physical limit of performance and a newer technology in the shape of electronic cash registers were poised to overtake the market with dramatic effect on the NCR company. In 1970 the market was positioned at a 90/10% split with electronic cash registers at the lower end, but this shifted to a complete reverse position of 10/90% just four years later. As a result of this battle of technology S-curves, NCR had to scrap $140 million of obsolete registers and lay off 20,000 workers in its manufacturing plants (1986, pp.139–141).

Foster argues that the S-curve theory can be used as a very useful forecasting tool which can help companies to assess what particular S-curve stage an innovation is at and thereby take appropriate action in terms of funding, increased R&D efforts or other measures. Foster's work is further developed by Christensen (1997) who provides a more nuanced picture in relation to characteristics of the technologies that are involved in S-curves series. Christensen introduces the notion of 'disruptive innovations' as well as 'sustaining innovations'. Sustaining innovations are the incremental improvement to a technology usually within an existing value chain, or innovations that are carried out within large companies as part of new product introductions within an already developed market. In contrast, Christensen describes disruptive innovations as those that emerge in new, often niche, market sectors with products that, at the time of introduction, may be lacking in some features but are available at a relatively low cost. These innovations initially follow their own S-curve trajectories within a niche market, but then have the potential to disrupt other larger established markets with potential dramatic effect. Christensen provides a number of examples of disruptive innovations that include the emergence of the PC (disrupting the main frame computer market) and small hydraulic diggers, which disrupted the market for large cable operated steam shovels (1997). Using Christensen definition, the emergence of low cost 3D printers (predominately in the shape of RepRaps and RepStraps) is a classic example of a disruptive innovation. While Christensen presents a very narrow definition of disruptive innovation, the term is now being used much more broadly to describe technologies and innovations that create new markets and disrupt existing commercial structures.

In 2013, The McKinsey Global Institute published a report on disruptive technologies and identified and analysed a number of technologies which 'could have massive economically disruptive impact between now and 2025' (McKinsey Global Institute, 2013, p.2). The view of 3D printing (or ALM) as a disruptive technology is illustrated by the technology’s inclusion in this report.

In this report the Institute identifies and analyses a number of technologies which 'could have massive economically disruptive impact between now and 2025' (McKinsey Global Institute, 2013, p.2). McKinsey selects 12 technologies that meet the institute’s criteria. Of these technologies, only 3D printing (and Advanced Robotics to a lesser degree) relates directly to digital fabrication. Despite significant media hype the potential economic impact of 3D printing according to McKinsey’s report is relatively modest compared to other technologies, such as the 'Mobile Internet' and the 'Automation of Knowledge Work'. McKinsey estimates the two latter categories have a potential economic impact of 3.7 to 10.8 trillion dollars each, while the economic potential of 3D printing is estimated to constitute between 0.2 to 0.6 trillion dollars (McKinsey Global Institure, 2013, pp.11–13). While it is significant that digital fabrication (particularly in the shape of 3D printing) is included on McKinsey's list, the expected impact of this group of technologies in this report is considered far less than other commentator's predictions. These include Anderson (2013) and Desjardins (2014) who have argued that 3D printing is still in a very early stage in relation to innovation trajectory. Therefore, the innovation impact of this technology still largely comes with the expectation of a very dramatic impact in what is being termed a 'new industrial revolution' (Anderson, 2012; Barnatt, 2013; Design Museum, n.d.).

As an illustration of these expectations Desjardins (2014) compares the rate of diffusion of 3D printers with that of personal computers in an assessment based on Roger's S-curve. In this comparison the number of PC's in the US reached one per inhabitant in 2010, while based on the current number, 3D printers are not expected to reach the same level of diffusion until 2040. As a consequence Desjardins identifies 3D printing technology as being at the very start of Rogers's bell and S-curves. Such a positioning implies that the market for 3D printers would eventually be the same as that for PC's. The notion that 3D printing could mirror the diffusion for 2D computer printing or desktop publishing has frequently been proposed in the media coverage of 3D printing.

Additional reflections on S-curve theories are included in the discussion of this thesis. These reflections conclude with the researcher proposing a theoretical contribution by presenting a model that seeks to represent the current situation in relation to some common digital fabrication technologies.

5.5.2 Other Contextual Developments

Due to time constraints many contextual developments have not been investigated through this study, but which the researcher still recognises as being significant to note. These factors include funding and aspects of the current business environment, which are considered to have a considerable impact on the overall environment for independent innovation.

In this regard there has been a number of significant recent developments, which impacts particularly on the field of digital fabrication. Examples of these are the new commercial opportunities that are being presented through the growth of online market places. In particular, these include services for build-to-order digital designs via 3D printing, such as those run by *Shapeways* and *Kraftwurx* (Kraftwurx, Inc., 2014). Equally, crowdfunding sites such as *Kickstarter* continue to provide funding opportunities for independent innovators. 3D Hubs B.V. have provided an number of detailed surveys on crowdfunded 3D printing projects, estimating that the total yearly funding via this source would reach $10 million in 2014 — a ten-fold increase from the total figure in 2011 (3dHubs B.V., 2014). The notion of crowdfunding is discussed at some length in the initial contextual review, but it is relevant to reiterate the impact this funding platform continues to have on the field of digital fabrication and independent innovation in general.

While it has not been within the capacity of this research to provide extensive research into issues regarding innovation funding and commercialization, the researcher considers these also as being potential significant factors, which could be the subject of further research.

6 Methodology

There is a close correlation between the subject of this research and the main methodology of this study, that of practice-based research. This chapter will discuss this relationship and the rationale for the use of this particular methodology. However, the study has also (to a minor degree) involved other research methods such as empirical testing and a semi-structured interview. These methods are also described in this section.

Finally, this study (alongside another of the researchers' projects) has been the catalyst for the researcher developing a new type of research journal, which can aid the use of practice-based methodologies alongside quantitative data collection. This research tool has been created as a database template operated on IOS devices in the FileMaker Go App environment (Apple Inc, 2012). This tool will be presented at the end of the methodology chapter alongside a description of its use in this study.

6.1 Practice-based Methodological Overview

This study is centred on practice-based investigations of the RPT concept, with a particular emphasis on a methodology of research and discovery through practical experimentation.

As highlighted in the introduction to this chapter, the rationale for this research project is closely connected with the selection of this methodology. The premise of this research is that digital tools facilitate new opportunities to enable outsider innovators to contribute with different perspectives, knowledge bases and approaches. The value of such external actors in the innovation scenario has been highlighted in the contextual review and supported by scholars such as Pursell and Smith (1994; 2005). In addition, the researcher also contends that it is not only the increased access to tools and knowledge resources that is significant, methodologies and development approaches from other fields, such as creative practices, could have an equally strong potential to contribute in innovation scenarios. Methodological approaches in this sector are typically 'inductive', where theory and knowledge are seen to develop though observation and exploration, rather than through a 'deductive' methodology, where experiments are used to validate a pre-determent theory (Cohen et al., 2007).

Barrett describes the inductive approach as an ‘emergent methodology’ with particular reference to research based on creative practice where theory predominately emerges from practice (Barrett, 2010, p.6), or where practice and theory develops in close synergy — a process that Bolt (2010, p.29) titles 'double articulation'. Bolt also highlights the value of tacit knowledge and the contribution that creative arts practices can bring in terms of research and discovery to many fields (Bolt, 2007).

As a case study, Bolt (2010) provides David Hockney’s research into the use of optical aids by sixteenth and seventeenth century European painters. Bolt argues that it was Hockney’s experiential knowledge developed through his work as a practicing artist that facilitated a particular insight, which established an entirely new understanding of these works of art — an insight which was further supported and developed by practical experiments by Hockney (2006). Bolt agues strongly for the value of knowledge developed through first-hand experiences of process and material, and advocates Paul Carter’s notion of ‘material thinking’ (Carter, 2004) – which describes tacit knowledge as that developed through practical and creative practice. Bolt also quotes Martin Heidegger's (1966) notion of knowing the world 'through handling' (Bolt, 2007, pp.30, 33), and highlights Heidegger’s belief that ultimately all theory has roots in practice or ‘handling’ rather than contemplative thought (Bolt, 2007, p.30).

The researcher’s profile corresponds closely to the notion of a practitioner with high levels of ‘material knowledge’ developed through direct experience and practice. The researcher contends that this position presents a strong potential for contributing with useful insights in a research and innovation scenario in digital fabrication. The potential for the creative practitioner to be at the *heart* of a research process is also highlighted by Gray and Malins (2004) describing this as a 'naturalistic inquiry', which position the practitioner/researcher in a *natural*, real life, setting, again drawing on key elements such as 'tacit knowledge' and 'emergent methodologies' (Gray and Malins, 2004, pp.72–73).

In large parts, these concepts build on the work by Schon (1983) concerning the notion of reflective practice. Schon broadly categorises reflective practice in two core aspects ‘reflection *in* action’ and ‘reflection *on* action’. 'Refection *in* action' is described as the ability of experienced practitioners to react responsively and intuitively to new situations or problems. While ‘reflection *on* action’ is the subsequent critical evaluation of the situation (Schon, 1983). A key concept in Schon’s theories is the notion that reflective practitioners have the ability to construct their own theories in order to explain and respond to unique situations, rather than just relying on established knowledge. Schon discusses how a situation can provide ‘back-talk’ to set up a scenario where practitioners are seen to respond to challenging tasks through a ‘reflective conversation’ with the situation (1983).

Schon also appears to provide a level of critique on certain professions’ ability to effectively operate in unfamiliar problem situations: in this Schon refers to professions in fields, which at times, have claimed a level of exclusive authority to knowledge. Examples are provided from professions particularly based in science-based fields such as: medicine, agronomy or engineering. Despite critiquing such professions’ reliance on *rigid* knowledge bases, Schon also presents examples of how such science-based professions can adopt a reflective approach to their practice (1983, pp.168–203).

A methodology also closely associated with reflective practice and practice-based research is that of action research — where the practitioner is a centrally engaged and reflective researcher (Cohen et al., 2007, pp.297–313; McNiff, 2002). Knowledge gained through action research is intended to be implemented back into the practitioner’s own work through iterative cycles of planning, action, observation and refection. Action research is therefore predominantly a tool aimed at improving a practitioner’s performance and to generate new knowledge within the context of this practice. It is not necessarily a research approach which has to establish new knowledge in a wider context, although the methodology can be used equally well to generate original knowledge.

Diagrams illustrating action research methodology are presented below (see Fig. 23). Two models are presented with one illustrating a more conventional action research methodology, while the other represents a simplified model which contains less pre-planning. The latter model was frequently used by the researcher during the practice stage of enquiry of this study. In this work to develop of the RPT concept, formal planning stages were minimised to enable rapid cycles prototyping activity.

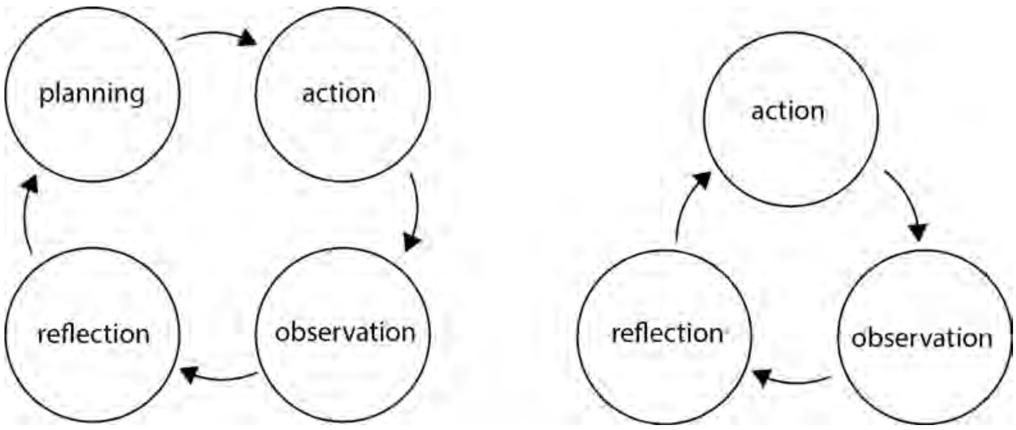


Fig. 23 Illustrations of action research methodologies, after Elliot (1991) and McNiff (2002). Conventional action research model illustrated on the left and a simplified model frequently used by the researcher illustrated on the right.

6.2 Methodology Rationale and Interrelationship with Practice Elements

As previously highlighted, this study contains two main strands of practice. One strand was focused on developing an RPT system through the engagement with local industry, which resulted in the development of an RPT system for shaping upholstery foam. The other practice strand focussed on a artistic exploration of the RPT concept within the researcher’s own design practice. The role of this investigation was to facilitate a wider, more open-ended, creative explorative of the RPT concept. The researcher contends that this part of the study has a value in its own right by producing artefacts and ‘situated knowledge’ (Barrett, 2010, p.2). Equally, this strand was also intended to perform a particular role in relation to the other practice strand which was aimed at exploring the RPT concept through industry engagement. This role concerns the concept that experiences and knowledge *from the outside* can have significant impact on the innovation scenario by feeding idea generation and potentially enable moments of insight. The notion of drawing inspiration from such external sources in the innovation scenario is highlighted in literature and have been discussed in the contextual review. (Pursell, 1994; Smith, 2005).

In this regard, it is also relevant to highlight that the two practice strands were not intended to represent or investigate opposing methodologies, and it is important to reiterate that both practice strands were essentially developed with an underlying practice-based research approach. While the foam RPT investigation also contains elements of empirical testing, the emergent methodology used during the development of the system was not different from that employed in the development and creative exploration of the glass RPT system. Rather than attempting to construct a study where different methodological approaches could be tested in a comparable study, the intention with the two practice elements was to have complimentary investigations, which could cross-fertilise each other in order to build up the overall knowledge base that would answer the researcher's question.

A tangible example of such cross-fertilisation was the development of the IOS database templates to assist the research. It was the needs of the glass RPT investigation which initially spurred the researcher to instigate the construction of this research gathering approach, however, much of the subsequent development of this tool was carried out during the foam RPT investigation.

Both investigations benefitted significantly from the use of this tool in a number of ways, especially as a general research journal to record a wide range of data and observations. These databases were also equally useful tools to facilitate and enhance the researcher's reflective practice. Furthermore, the database templates that were developed were also employed as very effective methods for capturing empirical data during the testing phases of the research. The following subsection will describe development, rationale and use of the research tool in some depth.

6.3 The Development of IOS Based Research Database Templates

As previously shown, the main methodologies employed in this PhD study are those associated with practice-based research, reflective practice and action research.

While the notion of reflection, both in and on practice (Schon, 1983), is widely considered to be at the core of practice-based research methodology, it is the researcher's view that in order to fully utilise the notion of reflection, a supporting structure to enable the generation and recording of knowledge should be employed. The IOS database template was an attempt to create a tool which could assist in establishing a more effective and structured use of reflective practice.

In addition to strategies of structuring and recording reflection, other tools for gathering both core and supporting data were also explored for this study. In the early stages a number of ways of recording and organising both core and, more peripheral, supporting research data were investigated. An Initial approach was the use of a private blog to gather together various research data, but this approach proved somewhat unsuccessful as it was found that the standard blog templates did not fully correspond with the data gathering needs in this research study. Equally, the process of entering data on the blog via a personal computer was often not possible in many of the research environments, which included dirty workshops and field work with limited Internet connection. The researcher recognised the potential for establishing a new approach to data collection, which also combined a more structured use of reflective practice. It was envisioned that such an approach could be achieved in the shape of an enhanced database on a portable device capable of collecting a wide range of data streams into comprehensive reflective journal entries.

The basic notion of a reflective research journal has long been established. Gray and Malins (2004) argue that such a journal is a very good tool to structure reflection and also gather other supporting research material and data. Inspiration was taken from the notion of a comprehensive and well functioning research journal to start the development of a new type of rich, media-enabled, database template to help data gathering for this study. Gray and Malins discuss how digital technology can be employed in this task (for examples via the use of databases and digital photography), and highlight Bunnell's (1998) use of computer databases in practice-based research. However, significant technological advances have since taken place since the publication of Gray and Malins' book (2004). These advances enable new, and potentially more comprehensive concepts for research data collection, storage and retrieval. In particular, the capabilities of mobile computing in the shape of smart phones and tablet computers have developed dramatically. The researcher recognised the potential presented by these technologies and set out to explore the development of a research journal, which also could utilise the rich media capabilities of these devices.

The development of the database template was instigated during the researcher's creative investigation of the RPT for creating glass bowls. In this investigation paper-based templates were initially used to record production details when creating the glass pieces. These details included a range of key numerical research data, such as firing ramps, top temperature, glass size, mould position, etc. The paper templates also included fields for more circumstantial information such as date, location and kiln type. Equally, the templates had dedicated sections for the researcher to comment and reflect on the results of a particular test. Filling out these test forms inevitably meant repeating many details, which while still relevant, might not have changed from previous tests. Completing the details of circumstantial data (such as date, time, location, etc.) was also a somewhat repetitive and tedious task. The time needed for completing such details on a paper based form meant that the researcher would be less inclined to spend time on recording comprehensive reflective comments. And while extensive photographic records were kept of the making process and end results, there did not appear to be an easy way of linking the paper based records with the digital images.

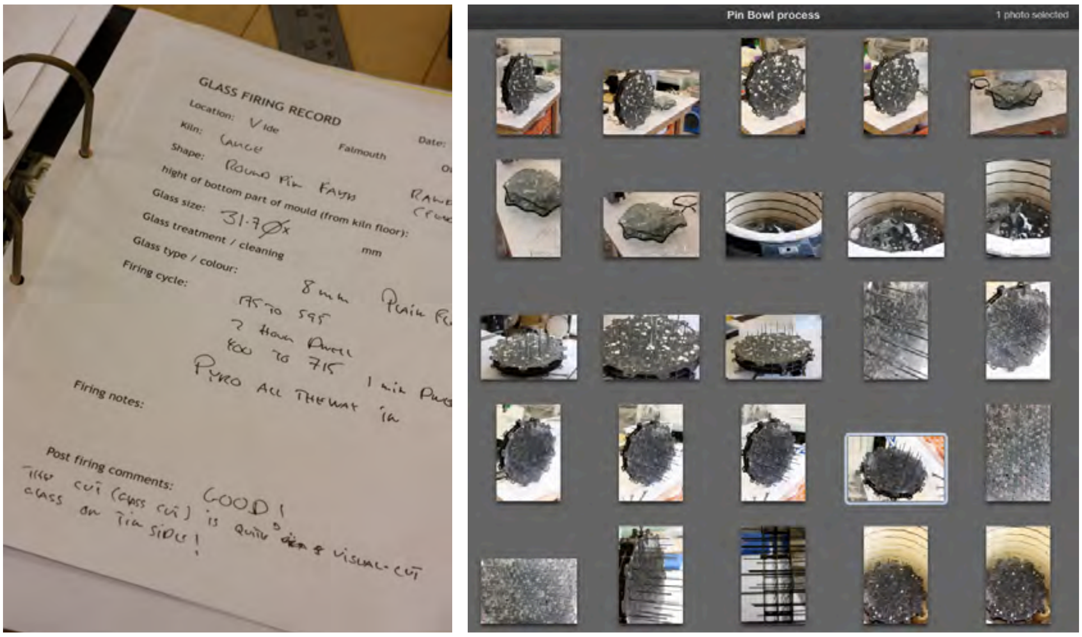


Fig. 24 The paper-based templates and image collection initially used by the researcher to record details of the glass RPT investigation, photo: T. Jørgensen, 2011.

In response to this situation the researcher started to explore the use of IOS based databases to record the data steams for this research work.

Initially, the priority was to replicate the paper forms to create a simple way of gathering core data from the investigation. However, during the process of creating the initial database template, it was realised that there was a potential for creating a much more comprehensive data gathering tool. In this regard, the researcher became interested in the notion of ‘thick description’ developed by the anthropologist, Clifford Geertz (1973). The concept of 'thick description' is an approach of documenting not just core research data, but also much wider context and circumstantial observations.

Inspired by this notion a database template was developed, which was intended to gather a wide range of information about a particular test compiled into one, comprehensive database entry. Another objective with this template approach was to create a tool which could facilitate a greater use of reflection in the research process and compile such reflections with the other research data.

The FileMaker software was selected as being a particularly suitable platform for developing a database template based on the researcher's vision. This platform was particularly appropriate as FileMaker databases can work seamlessly over a number of operating systems, including IOS based smartphones and tablets. This facility, alongside FileMaker's capability to deal with a wide range rich media formats, was of particular interest to the researcher. The rich media capabilities of FileMaker has long been established through the software legacy in personal computing that dates back to 1985 (Koenig, 2004). Another significant advantage of the FileMaker software is the software's What-You-See-Is-What-You-Get (WYSIWYG) interface. This interface contrasts with other database-building environments, such as 'Hypertext Preprocessing' (also known as PHP), which requires the use of programming code to build the database. Filemaker's WYSIWYG interface means that it is relatively simple for a novice to develop database templates. Consequently, individual practitioner-researchers that have no programming expertise can quickly gain the skills to create their own templates in response to a particular need or research project. Parallels could be seen here in the role that other development tools (such as visual scripting software) are having in lowering the barrier of participation in the many other design and innovation situations, as has been outlined in the contextual sections of this thesis.

The FileMaker software was initially developed for standard Apple and PC platforms but was brought to the IOS platform in 2010 with the introduction of FileMaker Go App (Apple Inc, 2012). This free App enables the use of databases designed in the FileMaker Pro version of the software to be used on IOS devices. The App enables the full use of the rich media capabilities of IOS devices such iPhones and iPads. Significantly, these rich media capabilities can be used to document the research in a wide range of ways such as: images, typed text, audio, movies, basic sketches and numeric data. This means that multi-threaded entries can be compiled as individual database entries, documenting the stages and results of a research enquiry in an extremely comprehensive way.

In addition to the direct recoding of research data in these media types, FileMaker templates also facilitate the import of other file formats into ‘media holder fields’. This facility may be a useful feature for some users, however, the native IOS media recording facilities were sufficient for this study.

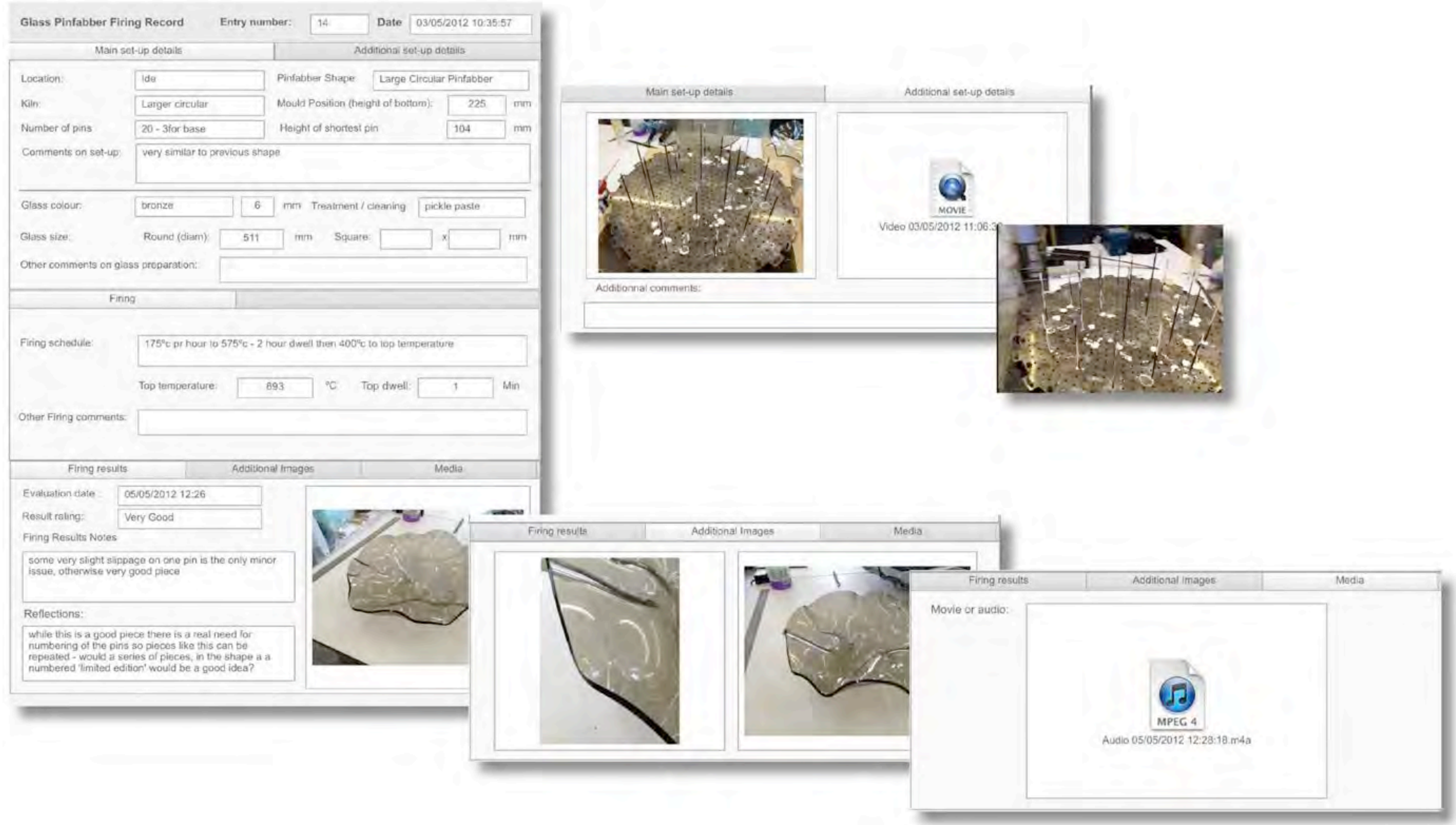


Fig. 25 An illustration of the IOS template with an example of a single research journal entry. The various 'leaves' has been expanded to illustrate the full multi-threated nature of the template. Reflective elements can either be added as text in the 'reflection' box or as audio in the field in the 'media leaf' – as illustrated. All media fields have the capacity to accept images, audio or movies.

As previously highlighted, a key objective with the IOS research journal approach was to facilitate an increased use of reflective practice. The intention with the IOS templates was to facilitate a more formalised reflective interaction with the on-going research subject. By this is meant an on-going analysis of the results to construct a continual 'problem-posing' structure to define, or re-align, the direction of the research.

This is a process that has been described by Gray and Malins as 'reflection for future action' (2004, p.57), and Schon as 'refection on action' or 'reflective conversation' (1983). In the templates developed in this study such reflections can be embedded within each journal entry and recorded in a number of formats including text, audio or movie. However, the researcher found the audio format to be the most appropriate, due to the ease of use and also the nature of 'free-flowing' reflections this medium seemed likely to facilitate.

The use of the IOS platform for a reflective research journal approach also presents other advantages, particularly in relation to the physicality of the IOS recoding device, which in the case of this study, was mostly the researcher's personal iPhone. The nature of this device is that it is very potable and can be readily *to-hand* in most research situations. As a result, research data can be recorded in close proximity and in 'real-time' in nearly all research gathering situations.

Furthermore, FileMaker Pro software enables the creation of usability enhancing features such as dropdown menus and auto completion of data fields. The researcher found such features to be very useful to enable a quick and efficient recording of circumstantial research data, such as date, location, research categories and key words. Dropdown menus, which can include frequently entered data sets, were also found to greatly enhance the usability of the template. Although the main database structure can only be edited on a PC with the *full* FileMaker Pro software, the dropdown menus can be freely edited 'on the fly' on any IOS recoding device during the research gathering. This feature offers a significant potential for a continual optimisation of the template in response to the data that is being collected.

Finally, having the research data entered directly into a searchable database offers very powerful tools in terms of viewing and analysing the recorded data. Such analysis facilities are not limited to the commercial version of Fliemaker software (Filemaker Pro) but a good number of search and analysis tools are also available within the free FileMaker Go App environment on IOS devices. This means, in effect, that a researcher can carry an investigation's entire recorded data in their pocket and readily access any part of it to inform further experiments and investigations.

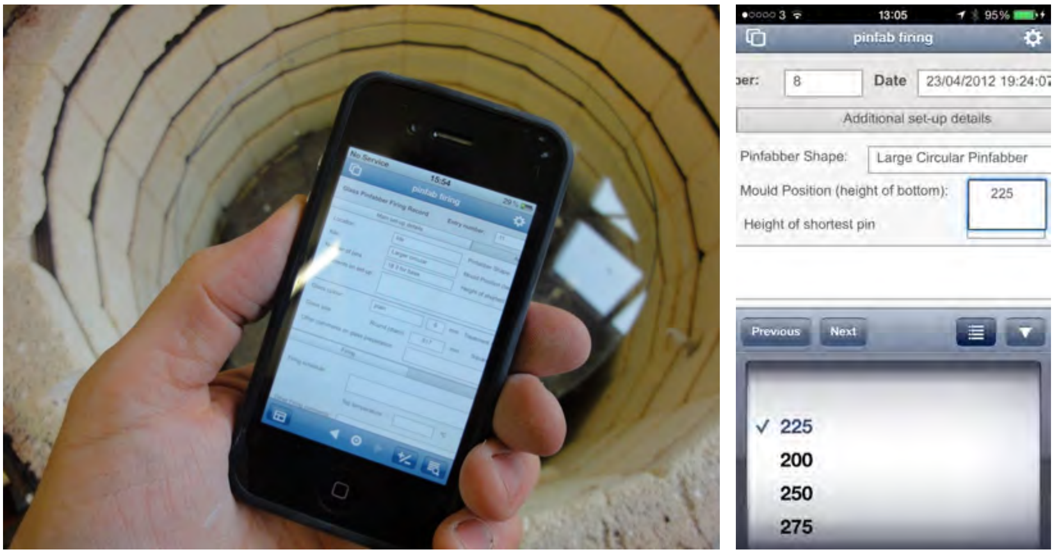


Fig. 26 An illustration of key aspects that help to enhance the usability of the IOS FileMaker Database concepts. The notion of the research recording device being *readily to hand* during the practice enquiry illustrated on the left, and drop down menus with frequently used data illustrated on the right, photo: T. Jørgensen, 2012.

The researcher developed a number of different IOS database templates in response to the various aspects of the study. Of these templates the most used was a general-purpose research journal template, which was used to record developments in the practice enquires, on-going observations, reflections, general notes and contextual information.

Two types of layouts were created for this template, with one specifically designed for the screen size and resolution of the iPhone. To reach a balance between fitting key data fields with efforts to achieve simplicity and minimising 'scrolling', the template was designed to the full width of an iPhone screen but with a slightly longer format, in a resolution of 320 by 620 pixels (this layout is illustrated in Fig. 27). The other format for this template was optimised for viewing on a laptop screen or as A4 paper printouts.

This layout was developed with the aim of capturing one particular observation with four key data describers at the top, including: entry number, research aspect, entry type and subject (as well as the date and time). Below these describers a text field was placed to facilitate the typing of a main entry text, or alternatively to record this text via the IOS platform's integrated speech recognition facility, SIRI. All the text fields in the template were designed to be capable of accepting an unlimited amount of words, which insured that entries were not constrained by a particular field capacity. Below the main entry text a media holding field was created. This field was designed to be capable of holding a variety of rich media data such as images, movies or audio files. Such media fields also have the capacity to import files from other sources as well as entries via a very basic finger-sketching facility. This layout was duplicated five times as accessible 'leaf' tabs to enable the recording of further supporting data within the same entry. A smaller text field was included under each of these media fields for labelling and short explanatory notes.

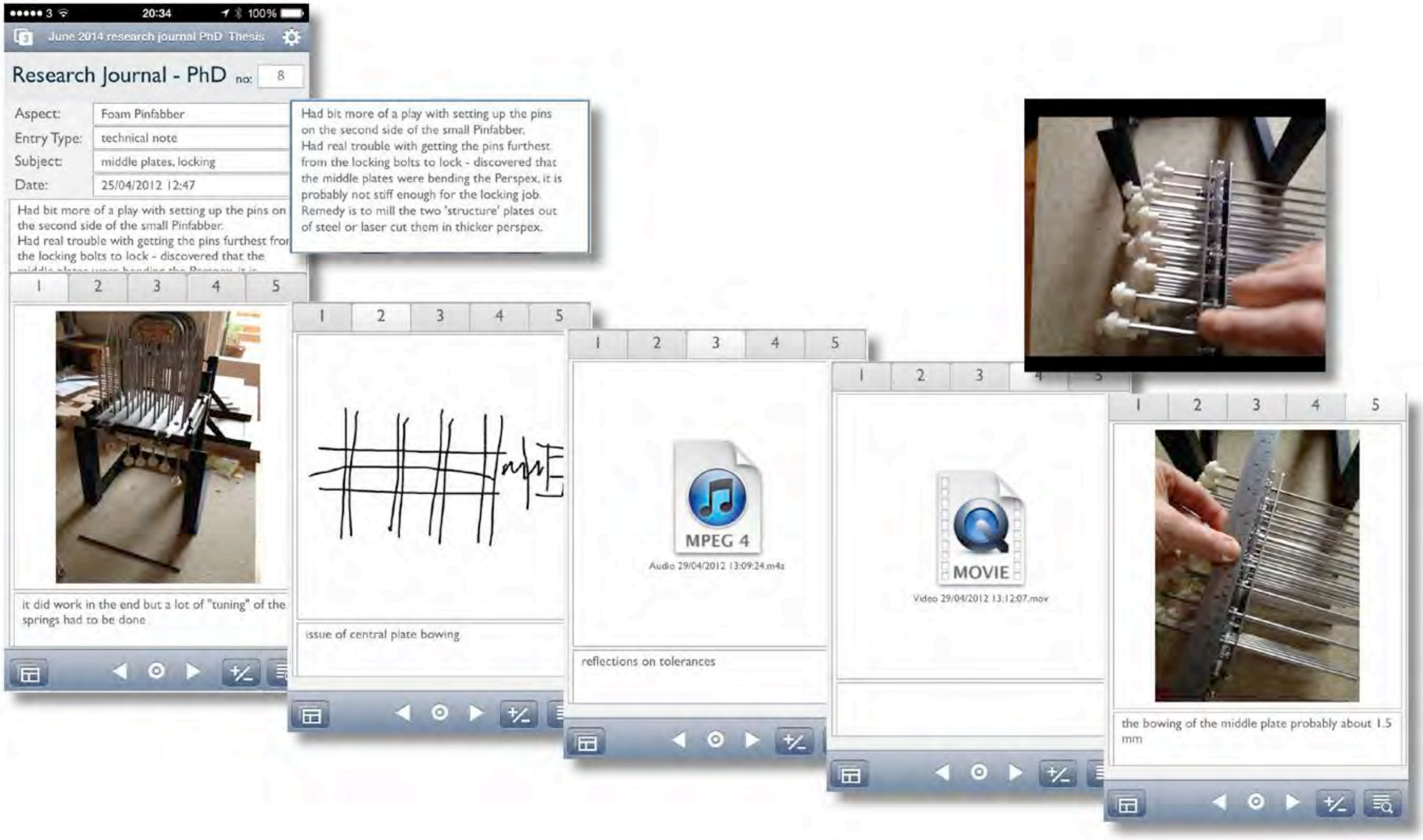


Fig. 27 The general-purpose IOS research journal template, illustrated as iPhone screen shots with the five layouts leaves expanded. The main text (and a still from an embedded movie) are shown in an fully expanded format.

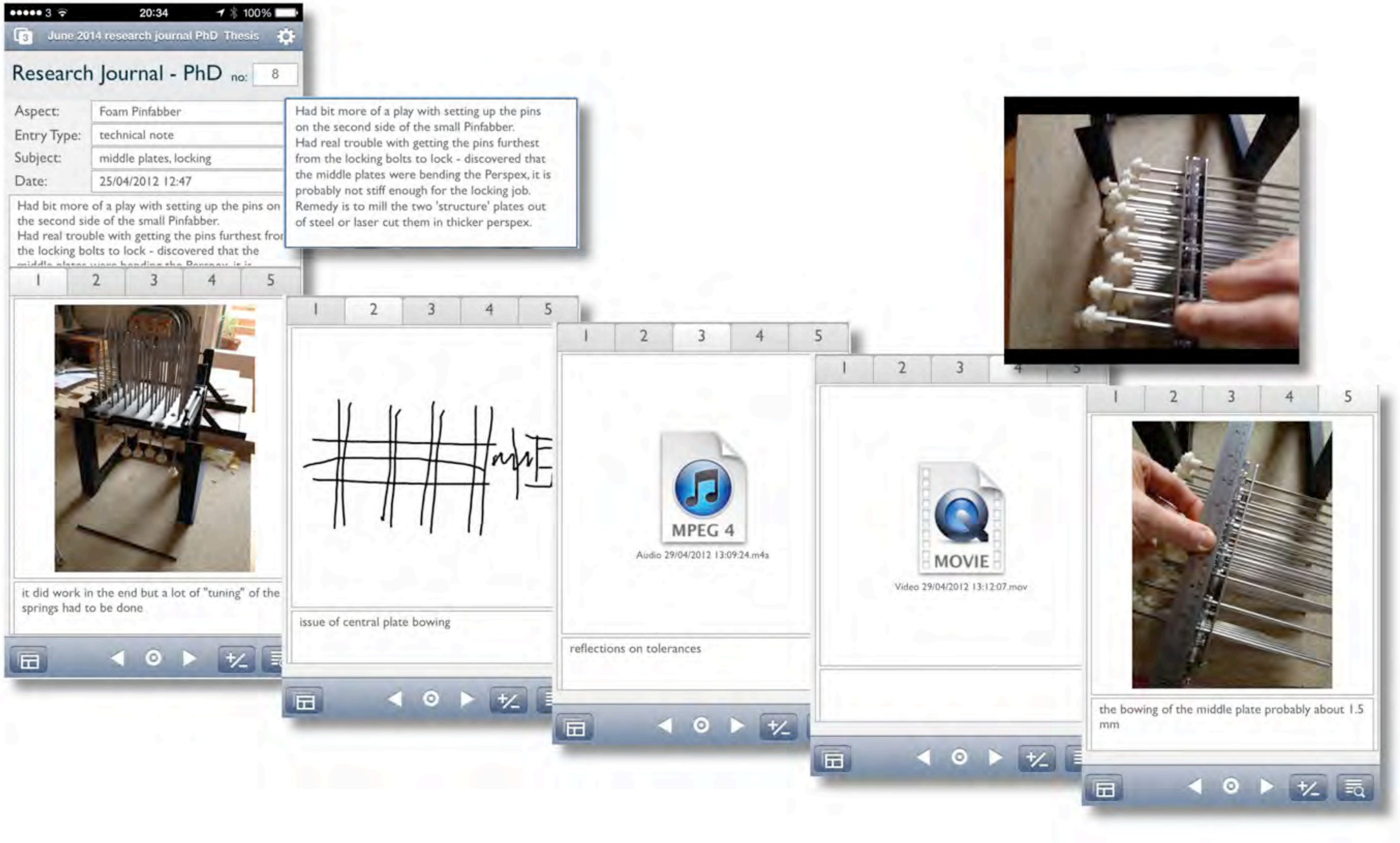


Fig. 27 The general-purpose IOS research journal template, illustrated as iPhone screen shots with the five layouts leaves expanded. The main text (and a still from an embedded movie) are shown in an fully expanded format.

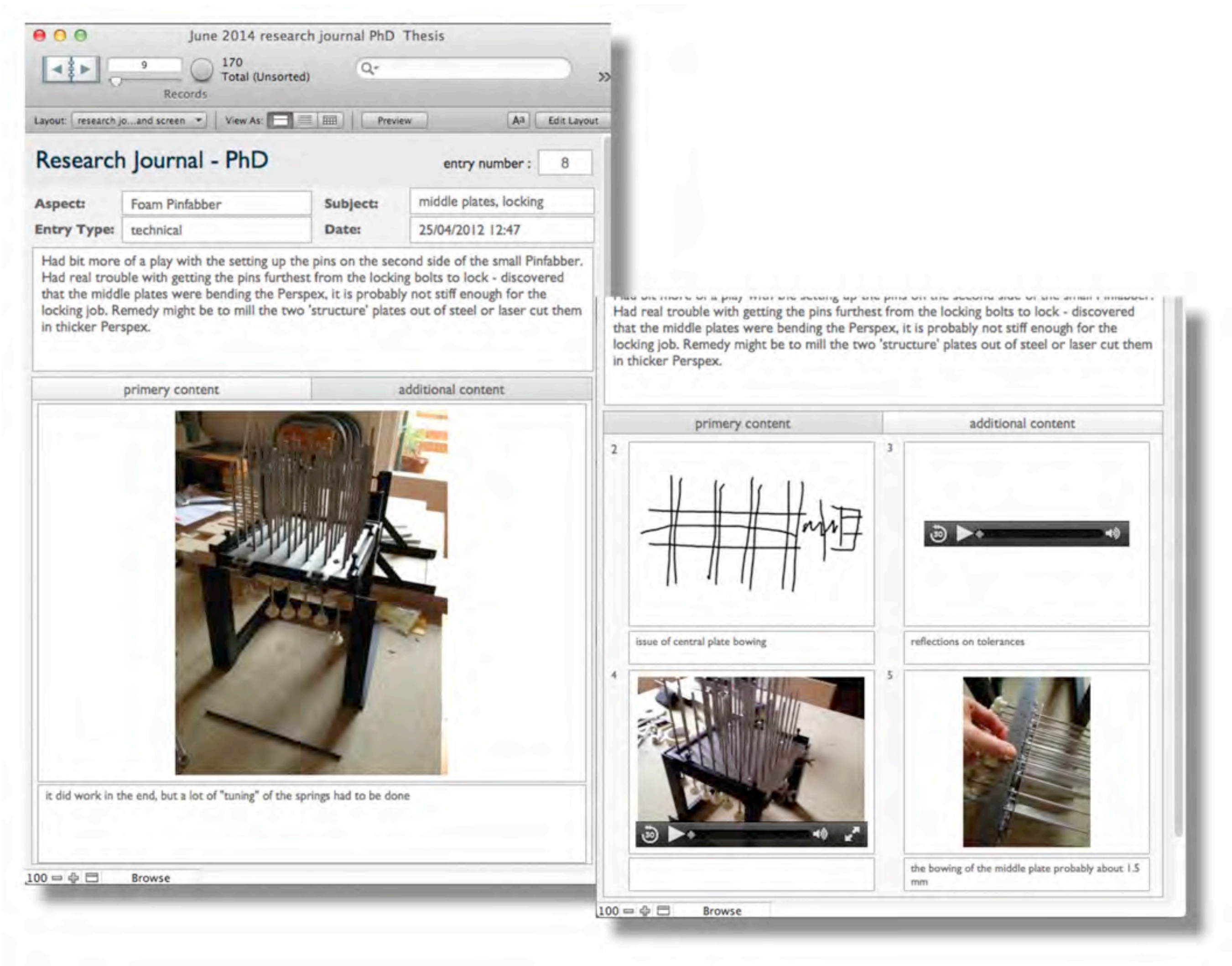


Fig. 28 The same data entry as illustrated in Fig. 27 (in the IOS format) but here shown in the 'screen and print-out' layout. The additional content leaf is shown expanded.

In addition to the general research journal template and the initial glass RPT firing template, a database template was developed to record the testing of the foam RPT device. This template will be presented in the subsection specifically concerning the testing of the foam RPT system.

In summary, the researcher found this new type of IOS research journal to be an extremely valuable (and even enjoyable) tool to use. The researcher has employed this data gathering approach for other research investigations, and presented the development and use of the IOS journal tool through a number of papers and presentations (Jorgensen and Matthias, 2013).

6.4 Prototyping

Much of the practice enquiry of this study has focussed on developing the RPT concept through physical prototyping and in this regard it is important to highlight that the wider notion of prototyping is considered to be an integral part of the practice-based research methodology employed in this study.

Physical prototyping has overwhelmingly been the core of the *inductive approach* adopted for the study. To highlight this point (and reiterate the introductory text to this subsection) prototyping was not employed merely as a process to develop predetermined systems to be tested in subsequent research investigation. On the contrary, it is critical to consider the prototyping process as a key feature of the knowledge generation aspect of this study. With such a key role in the methodology of this project, it is useful to explore the notion of prototyping a little further.

Michael Schrage, in particular, has explored the activity of prototyping in *Serious Play* (1999). In this book Schrage investigates many aspects of the notion of prototyping in terms of physical, electronic as well as more conceptual approaches. Schrage mostly views prototyping through the lens of innovation and business development. He starts his introduction by stating, 'Serious Play is not an oxymoron; it is the essence of innovation' (1999, p.1). Schrage clearly advocates the value of experimentation and ‘improvised’ exploration in an innovation scenario, or as he argues: ‘innovation requires improvisation' (1999, p.1). He clarifies the statement further: 'Serious play is about improvising with the unanticipated in ways that create new value' (1999, p.2). In the foreword to *Serious Play* Tom Peters frames the essence of Schrage’s advocacy of innovation fuelled by prototyping as a 'Ready, Fire! Aim' approach, clearly referring to the notion of gaining knowledge through active testing and observations rather than pre-planning and theory.

Throughout the book Schrage advocates the notion of 'rapid prototyping', a concept which does not refer to ALM technology, but to the notion of rapid iteration of ideas through experimentation and 'play' with models, simulations and prototypes (Schrage makes little distinction between these terms). He also highlights the notion of the use 'quick and dirty' prototyping, (1999, pp.18–19), particularly as a means of articulating an idea.

Serious Play was first published in 1999 and therefore predates the high level of diffusion in digital fabrication technologies that was initiated in the mid to late 2000s, which facilitated a widespread access to digital prototyping tools (in particular, ALM technologies). However, Schrage's book still explores how new technology can alter tools and approaches that can help to facilitate better prototyping activities (1999, pp.95–96), and ultimately better innovation and economic return. Schrage also highlights the value in using both physical and virtual prototyping by stating the potential for these to aspects to 'create design dialogues between CAD representation of products and their physical counterpart' (1999, pp.206–207). Schrage also predicts how the diffusion of digital design tools can help to enable a democratisation of innovation (1999, pp.167–169), predictions which appear to have had some accuracy.

Schrage offers insights into a range of approaches within the wider notion of prototyping, from generating ideas and concepts through 'crude muck ups' (1999, p.64), to the creation of more refined and formal prototypes. Schrage also describes potential problems in the relationship between a company's R&D activities and its full-scale industrial production. He provides an example of a diaper manufacturer where the prototyping activities in the R&D department were de-coupled from production line, which in turn was too rigid to adapt to further iterations and innovation in the product (1999, pp.139 – 140). This example was of particular interest to the researcher, as one of the attractions of the RPT concept is its flexibility and therefore strong potential for undertaking continuous production iterations. Schrage highlights the need to establish manufacturing systems where product iteration can be continuous without any significant loss of productivity, and advocates manufacturing systems which allow for a high degree of experimentation or 'serious play' to enable the design and development of entirely new products.

Parallels with the 'ready, fire! aim' approach and many of the prototyping concepts explored by Schrage, can be drawn with approaches evident in the Hacker and Maker-Movement subcultures, which have central relevance to this study. In particular such notions can be seen illustrated in the 'Cult of Done' manifesto by Pettis and Stark (2009), which clearly advocates the notion of experimentation and quick fire prototyping. The use of such approaches is described by Pettis in van Abel et al. (2011). Pettis' role as a central figure in the development of the RepStrap Sector and growth of independent innovation in the digital fabrication in general, is discussed extensively in the contextual review of this thesis.

Throughout this study the researcher sought to explore and recognise the various stages of prototyping activities and adopt particular prototyping methods according to a particular stage of development. For example, initial concept-building prototyping activities were developed quickly in low fidelity, while at later stages much more refined and precise prototypes were needed to ensure the highest degree of functionality in the RPT systems. These prototyping methods and stages are further discussed in the chapter covering the practice enquiry of this study.

6.5 Other Research Methods

While this study is predominately structured through the use of methodologies associated with practice-based research, other research methods have also been employed in supporting roles. The following subsection will briefly outline these methods, the rationale for employing them, and the tools used to record the data from this aspect of the study.

6.5.1 Scoping and Fieldwork

Elements of scoping and fieldwork were undertaken throughout the study but a particular intensive activity was carried out in the early phases of the project. The scoping activities took the shape of meetings with individual practitioners, site visits to small companies, interactions with third sector companies, attendance to conferences/symposia and other face-to-face networking events. These activities were carried out to identify applications for the RPT concept, to find industry partners and generally inform the researcher of the field of study.

During the scoping and fieldwork sessions information was gathered through methods such as informal interviews, discussions, observations and recorded through photography, note taking and audio recordings.

6.5.2 Empirical Testing

As highlighted in the introductory text, this study is based overwhelmingly on qualitative data gathered through practice-based research rather than quantitative data captured though empirical studies. However, in order to accurately assess the performance of the foam RPT system some structured empirical testing was carried out on the last series of tests (Key Stage 2) of the RPT foam system. Accurate measurement of this series test was taken and analysed in relation to the digital design data and other tests in the series. Rates of accuracy and production repeatability were calculated on the basis of these figures. While only a relatively small number of tests (18) underwent such empirical testing, this element provided very useful quantitative data that complimented an otherwise qualitative study.

In relation to the gathering of supporting quantitative data the researcher believed it is relevant to again highlight the capabilities of the IOS database templates that were created to record the data of this study.

Both during the glass RPT investigations and the testing phase of the foam RPT system, the IOS templates facilitated a very effective gathering of supporting quantitative data. In addition to core empirical data, other aspects of the research, which could be characterised as *circumstantial*, were also captured. Such data included test location, date, time, etc. And while such circumstantial data may seem less relevant at the time of research gathering, later analysis might find such data to have increased in importance than first anticipated. The facility of easily capturing such a wide range of data directly into a powerful database structure makes potential retrieval and use of such data for future research purposes far more likely, regardless of whether the use is focused on qualitative or quantitative studies.

6.5.3 Research Methods in Relation to Interaction with Industry Partner

The interaction with the industry partner, MARK Product, was highly valuable to many aspects of this study, and throughout the study the researcher met with the industry partner on numerous occasions. Initially these meetings were undertaken as a part of the general scoping and fieldwork activities in order to gain further contextual evidence for the study, but particularly in relation to efforts to identify applications for a proposed RPT system that was yet to be developed.

It had been the initial intention to develop an RPT system to a level of maturity where it could have undergone real-life testing by the industry partner. By this is meant that a system (or the capacity of the system) would be created that would have been used independently by MARK Product. Such testing would ideally have taken the shape of a design and production project exploring the development of commercial products that utilised the advantages of the RPT concept, both technically and aesthetically. Such real-life testing was proposed to be structured and analysed with case study methodology (Yin, 1994), adopting a practice-led research investigation approach, where the focus is on research *into* practice (Rust et al., 2007). However, the foam RPT system did not reach a sufficient level of development where such a case study would have provided meaningful data for the study. Instead, the researcher presented results from his own testing and creative exploration of the RPT foam system to the directors of MARK Product. The intention for this aspect of the research was to get the most relevant and realistic feedback from an industry sector and commercial perspective. This presentation and subsequent discussion of the results of the foam RPT system was framed as a semi-structured interview. This method was considered as the most appropriate way of gathering data from concluding aspects of the industry interaction.

Since the RPT foam system did not reach a stage where it could be independently tested by MARK, a questionnaire was considered not to be an appropriate method of collecting the views of the industry partner. Equally, a fully structured interview would have carried the risk of not capturing peripheral, but potentially valuable observations and reflections. A highly structured interview was seen as an alien and rigid element in a research project, which from the outset aimed to harness the information gained from an enquiry with a high degree of reflection. In contrast, a completely unstructured interview would have carried the risk of not covering some of the key aspects, which had emerged as central themes through the other elements the research project, including the contextual review, fieldwork/scoping and the practice investigations.

In preparation for the interview the researcher prepared a list of topics he considered as key questions/topics to discuss. The location of the interview was chosen to be at the MARK Product office, with the researcher bringing physical examples produced during the foam RPT system investigation and tests. This location was deliberately selected to make the interviewee feel comfortable in their environment and potentially therefore more likely to provide honest and accurate insights.

To record the interview a digital HD camera was positioned to capture not only the dialog but also non-verbal interaction such as gesturing. The video footage was also intended to record potential ‘pointing’ to reference particular physical artefacts which may be the subject of parts of the discussion. However, the audio recording from the discussion was always considered to be the central source of information to capture during this interview, and this data was therefore recorded separately. A full description of the interview, including details of the topics prepared by the researcher, is included in chapter 8. This description includes the findings, key quotes and an analysis of the data.

Prior to the interview the industry partner was presented with documents concerning the ethical considerations, details of which are included in the following subsection concerning ethics.

6.6 Ethics

While this study did not present very significant ethical dimensions, some considerations and actions in this regard were still taken, particularly in relation to issues regarding Intellectual Property (IP) and also some consideration in relation to the recorded interview with the industry partner. As the interaction with MARK Product was, from the outset, predicted to be close, a Non-Disclosure Agreement (NDA) was signed with the company at an early stage to cover IP developed by the researcher during the duration of the study.

As already mentioned, the other main aspect of ethical consideration concerned the recorded interview with MARK Product. In this regard participant agreement forms were presented to both interviewees, explaining the purpose of the interview, how it would be recorded and the ethical considerations in this regard. Both the researcher and interviewees signed this form. A copy of this participant agreement form and the NDA template used in this study is supplied in the appendices of this thesis.

7 The Practice-Based Enquiry

This chapter will provide a description of the practice-based research activities undertaken during this study. These activities are focused on two main investigations: an exploration of the RPT concept to create glass bowls, and an investigation concerning the development of an RPT system for shaping furniture upholstery foam. As previously highlighted, the latter practice enquiry strand was carried out in consultation with a local furniture company, MARK Product.

Both of the practice enquiries were structured with a number of individual objectives specifically developed in relation to the particular strands. These objectives are detailed in the subsections covering each of the strands. The two practice strands were carried out in parallel with the intention of creating a situation where the stands would cross fertilise each other, and the researcher has created a graphic representation of the practice enquiry in the shape of a map which illustrates key stages of development (see Fig. 29).

Both of the RPT systems were developed through practical prototyping and experimentation rather than implementing a predetermined construction based on theoretical knowledge. The developmental process of these RPT systems are a very significant aspect of the innovation scenario investigated in this study, and consequently a detailed description of the two development strands are included in this chapter.

Firstly, the investigation that focused on exploring the RPT concept for creating glass bowls will be discussed. This subsection includes a description of the development of RPT systems, including all the various aspects involved in this work. This subsection also explores a description and discussion of the creative exploration of the system and the issues involved in this process. Following these sections is a subsection covering the development of the foam RPT system.

While both of the practice strands spanned a number of aspects, the development of the foam RPT system involved many more stages and elements. The researcher recognises that independent innovation in digital fabrication is highly likely to involve a multi-disciplinary approach with engagement in mechanical, computational, electrical and 'material knowledge' aspects. Several subsections in this subsection cover the development of these various aspects of the project. These include the various development stages, including: early concept exploration, development processes, interim testing, system refinement and concludes with empirical testing of the system. These stages again include various aspects such as the mechanical construction and creations of the CNC aspects of the system.

As a precursor to the development of CNC aspects, the researcher organised a CNC building workshop for a group of interested individuals at Falmouth University in order to gather technical knowledge and experience concerning generic issues with CNC technology. A subsection covering this workshop intersects the overall description of the development of the foam RPT system. Sections then follow concerning how the knowledge gained in this workshop was implemented in the construction of the foam RPT system including the developments of electrical and computation elements.

To inform the construction and refinement of the system a series of on-going tests were carried out, which are labelled as 'Key Stage 1' tests. The testing process also included the creation of a series of furniture seats complete with upholstery covering to explore the system's potential in a complete production sequence. After series of alterations and refinements had been carried out in response to the result of the Key Stage 1 tests, a final series of tests, Key Stage 2, was carried out to provide empirical data on the capability of the system. The aim of this testing phase was to assess the usability of the systems through tests concerning consistency and accuracy. The chapter concludes with an overall analysis and discussion of the RTP system.

Below (see Fig. 28) is a diagram that illustrates the development of the two practice strands through two parallel time lines. Whilst the following sections explore the practice strands singly to aid understanding, this diagram highlights the reality of them being undertaken simultaneously. It also highlights how each strand impacted and informed the other and should be kept in mind when reading the following sections.

Fig. 29 Graphic representation of the main developments in the two practice enquiry strands.

7.1 Exploration of the RPT Concept for Creating Glass Bowls

This subsection initially discusses the rationale and background for undertaking the enquiry. These sections are followed by descriptions of the various aspects of the construction of the two RPT devices that were created and tested during this investigation. The development process of this RPT application was rigorously recorded by the researcher in an effort to identify particular aspects of importance in this innovation process.

Reflections and commentary are provided within the description of the development of RPT systems in this practice strand. An overall assessment of the investigation in relation to identified objections follows the description of the development process, and the chapter concludes with an overall analysis and discussion of this stand of practice.

7.1.1 Rationale for the Investigation and Prior Work with the Concept

The primary role for this practice strand was to have an investigation that was located within the researcher's own practice sphere to provide data from an innovation scenario from this perspective and context. A particular advantage with this enquiry was also one of expediency. The researcher had, prior to this PhD study, already conducted some experiments with the concept of forming glass with an RPT system. These preliminary explorations had remained fairly primitive, but, nonetheless, these pre-study experiments enabled the researcher to initiate practical explorations based on an existing platform of knowledge with an RPT application that had a proof-of-concept already established. Documentation for the pre-study work can be found in papers published by the researcher (Jorgensen, 2010a, 2010b). These papers document the researcher's experiments of RPT for thermoforming sheet glass; a process also known as 'slumping' (Cummings, 2001). The aim of this pre-study research was to develop a system that could translate digitally designed surfaces into a physical material. Glass was selected as an appropriate medium to use with this concept as the slumping technique meant that only a single-sided mould would be needed. This is due to the particular process of glass slumping where gravity is used to force a glass sheet against a moulding surface while the material is being softened under the influence of heat. The glass slumping technique was particularly appropriate in this application as the pressure on each individual pin would, in this process, only be coming from the weight of the glass itself and thereby present modest requirements in terms of a pin locking mechanism. Furthermore, the temperatures needed for glass slumping are (in the wider context of glass forming) also fairly modest at 650 - 750 ºC; thereby presenting relatively modest refractory requirements on the system.

In addition to the technical advantages of using sheet glass in this exploration, it is also highly relevant to note that the use of this particular medium also presented the potential for creating pieces with high-level aesthetic qualities. This aspect was also a key consideration in terms of the material choice.

Fig. 30 Pre-study research exploring the RPT system for glass thermoforming, photos: T. Jørgensen, 2010.

The RPT system created and used in these pre-study investigations was constructed entirely in marine grade stainless steel. While normal (mild) steel will suffer damage through corrosions and distortion when exposed to the glass slumping temperatures, marine grade stainless steel (also known as SAE 316) is far more resilient. An RPT system constructed from this material will cope reasonably well with the temperatures needed for glass slumping and a complete moulding RPT module can be placed entirely within the glass kiln after the pins have been set to the required position — either manually or via CNC.

The pre-study work had established an early proof of concept with the RPT concept in combination with glass slumping, but no in-depth study of the possibilities with this approach were carried out, leaving an appropriate research opportunity for extending the investigation.

7.1.2 Framing the Enquiry and Identifying Investigation Objectives

This enquiry strand was intended to help to provide the study with a structure of multiple practice strands thereby enabling a situation where notions of how other experiences (especially in creative practices) can 'feed' innovation in other fields or sectors. The concept of drawing inspiration from outside elements in the innovation scenario is a reoccurring notion in this thesis and discussed in the contextual review and supported by literature on innovation theory (Pursell, 1994; Smith, 2005).
In short, it was the expectation that findings in the creative exploration of the RPT project would feed the innovation process in the development of an RPT system focused on applications for the local industry partner in this project. Another rationale for this practice strand was to provide a platform for the researcher to undertake more explorative investigations inspired by notions of 'serious play' approaches (Schrage, 1999), which have been outlined in the methodology chapter (subsection 6.4).

Unlike the pre-study work, the use of CNC in the pin setting process was not employed in a practice strand. At an early stage of this investigation is was concluded that the use of CNC with pin setting carried a risk of the investigation getting bogged down in technical challenges involved with this aspect. Rather than being focussed on innovation *in* digital fabrication this strand of practice would instead be focussed on innovation *through* or *with* digital fabrication tools.

An additional role of this aspect of practice was to provide a route for disseminating outcomes to academic and non-academic audiences. The investigation resulted in the production of a number of pieces that were entered into a commercial context through galleries and exhibitions, aspects that presented the researcher with the opportunity to explore the commercial potential of artefacts produced via an RPT system. In this context the term 'commercial' refers specifically to the commercial aspect of the applied arts sector, rather than a general commercial environment. Finally, this investigation played a valuable role as a test-bed for the development of the IOS based research journal template, described in the methodology chapter (subsection 6.3).

In summary, this strand of practice was driven by a number of objectives, including:

- To explore tools and factors in the innovation process.
- To explore the creative potential of the RTP concept in the context of designer-maker practice.
- To investigate RPT in a real life production situation and to explore the commercial potential for artefacts created via the system.
- To cross-fertilize with the other practice strand of the study.
- To test the potential for achieving a range of different aesthetics with a single RPT tool.
- To test the durability of an RPT tool in a practical production situation.
- To explore the role of the moulding medium in an RPT concept.
- To provide a test-bed for the development of a new digital research gathering and archiving method.
- To disseminate the research to both academic and non-academic audiences.

As previously stated, the exploration of RPT for creating glass bowls was intended to be explorative in nature with a strong focus on the artistic output. In response, a round RPT format was identified as an appropriate aesthetic format to base the exploration on. A circular matrix of pins was also a novel RPT approach (the researcher did not find any other RPT investigations based on such a pin matrix format through undertaking the contextual review).

7.1.3 Construction of the Glass Forming RPT Systems

To enable easy design iterations of the circular RPT devices a paramedic modelling script as a Rhino Grasshopper definition was constructed. This was done to enable experimentation with the pin matrix involving parametric variables that included the pin pattern, pin density and overall size of the device. The Grasshopper definition, developed for this purpose, was quite extensive in its capabilities, with a capacity for defining all aspects of the matrix plate into one file. Numeric sliders were included in the definition, which enabled details of the design to be altered, with the definition automatically adjusting other elements accordingly. At the outset, the aim was to achieve an RPT tool of 50 cm diameter, however, the size of the initially (smaller) RPT device was constructed with a 35 cm diameter to provide a manageable testing situation prior to the production of a larger device.

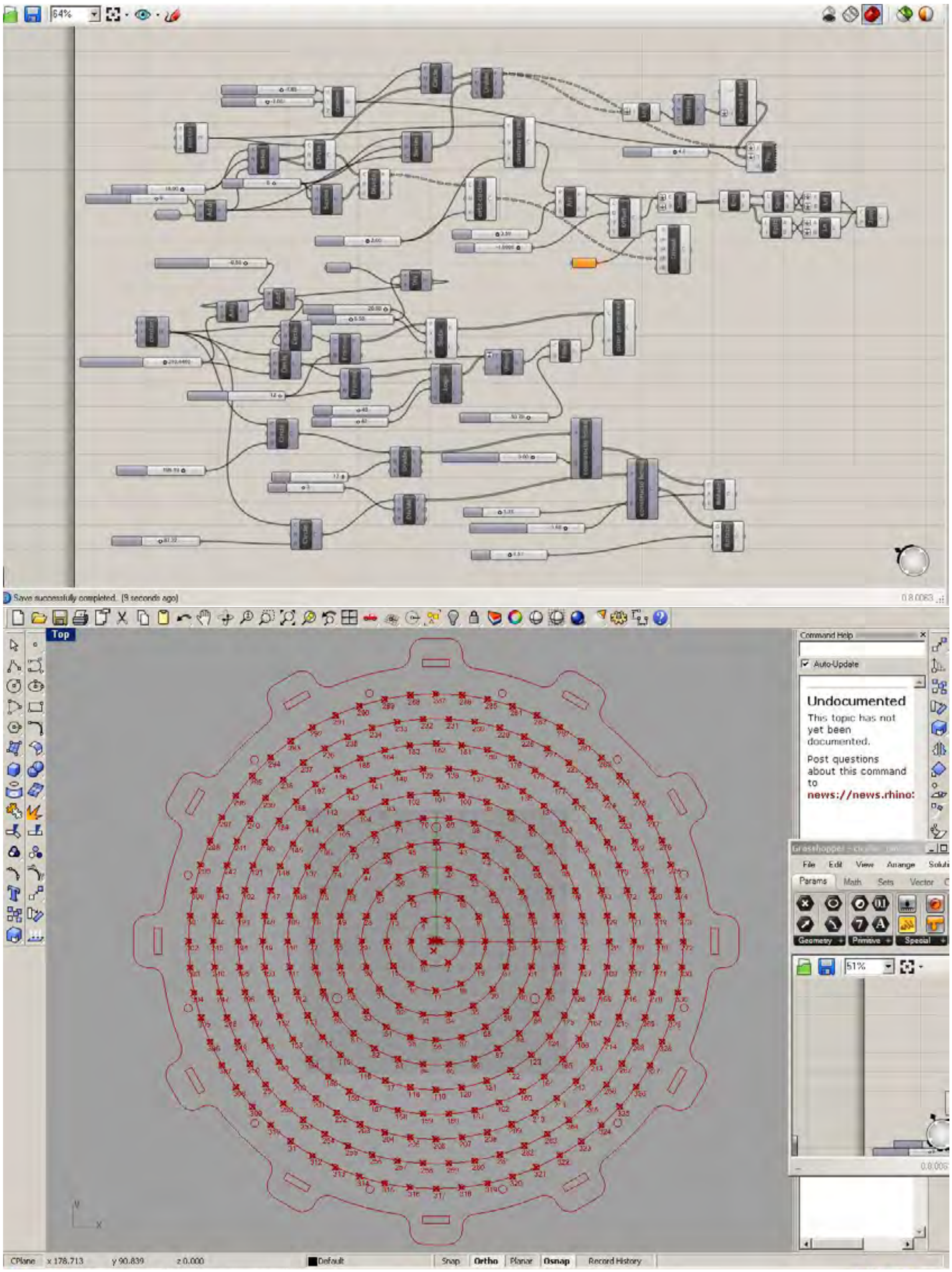


Fig. 31 The parametric Grasshopper definition developed by the researcher to create the files for laser cutting the matrix pates for the glass RPT systems. The matrix plate design, resulting from the definition, is visualised in the bottom image.

Whilst previous experience with glass forming via the RPT concept informed much of the design of the first round RPT device, experiments with this device also highlighted a number issues which were in need of improvement.

A key technical problem that was identified through experiments was an issue with the pin locking principle. The system was dependent on very high engineering tolerances to guarantee that all the pins were held in the friction lock. If the pins were not completely straight, or the holes in the matrix were either slightly misaligned or different sized, problems with individual pins failing to be locked in position emerged. This problem was aggravated by repeated use of the system. The 4mm diameter stainless steel pins used would generally perform well during the first few firings, but through repeated exposure to 700-750 ºC the pins would gradually start to distort and the friction lock, which depended on tight tolerances, would start to fail for some of the pins.

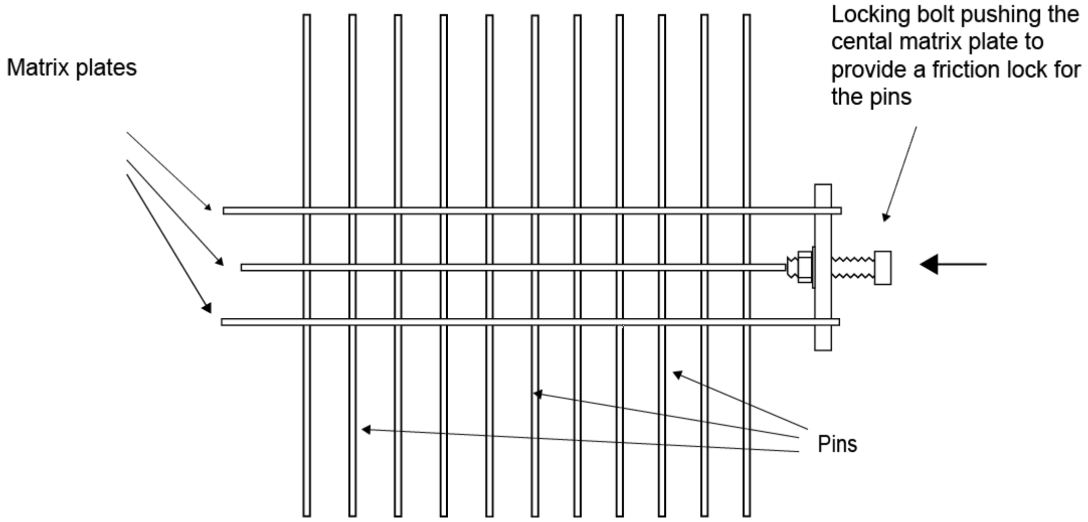


Fig. 32 The basic RPT friction lock principle used by the researcher in the early experiments of this study.

In response to this problem, the inclusion of a spring element in the locking element was proposed. This spring device was implemented as a semicircle cut around each pinhole in the middle plate (see Fig. 33).

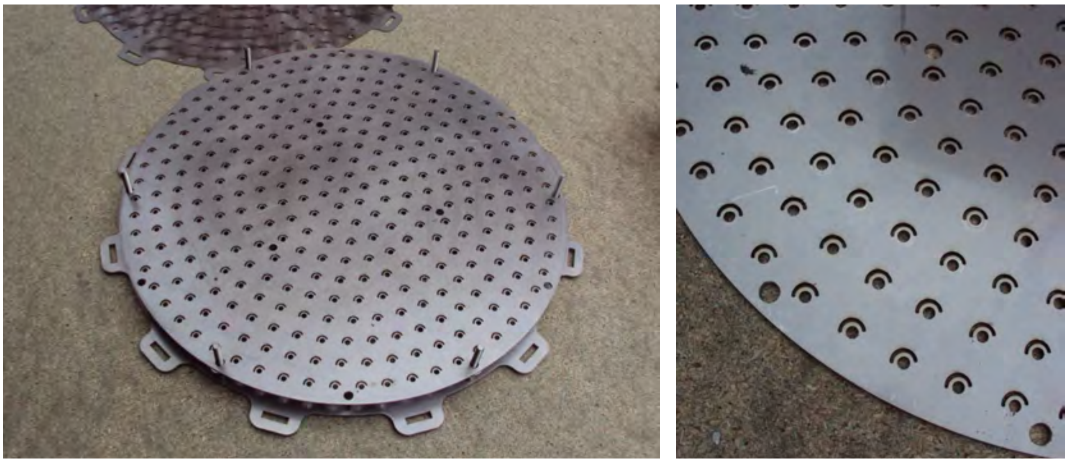


Fig. 33 The failed approach to integrate a spring element to the friction lock principle to the glass RPT systems, photos: T Jørgensen, 2010

A series of tests were carried out after implementing this improvement. These tests exposed other issues with the system; in particular, with the construction of the system for engaging and disengaging the central, pin locking, matrix plate. The areas of the middle plate, where the locking bolts engaged to apply lateral pressure, were found to be prone to buckling and distortion. It was also found that the overall construction of the friction lock had to be substantially improved to enable sufficient pressure to secure the pins firmly in their position during the glass forming process. During the construction of a second, and larger, circular RPT device, attempts were made to resolve these issues.

In response to these problems an improved locking mechanism was designed and implemented in the second iteration of the circular RPT device. In order to strengthen the middle plate on the part that the locking pressure was applied to, a new design for a fixing point was developed. This fixing point consisted of a series of small plates to create ‘stacked blocks’. These blocks were also designed to hold the locking bolt that would enable the lateral pressure to be applied. This approach also differed from the one used in the initial system, as the friction pressure would be applied through ‘pulling’ rather than ‘pushing’ of the middle plate (see Fig. 35).

Fig. 34 Assembling the improved locking points, which was created by layering sections of laser cut shapes bolted together to create a solid fixing point for the bolts, photos: T. Jørgensen, 2012.

The majority of the elements for the glass RPT devices were fabricated through laser cutting, carried out by a local company (Luffman Engineering). Many aspects of the device were deliberately designed with the laser cutting fabrication in mind, as this process presented the most affordable, high precession, digital, fabrication processes available to the researcher. One aspect of the RPT construction, which was not implemented through the laser cutting process, were the pin holes in the matrix plates.

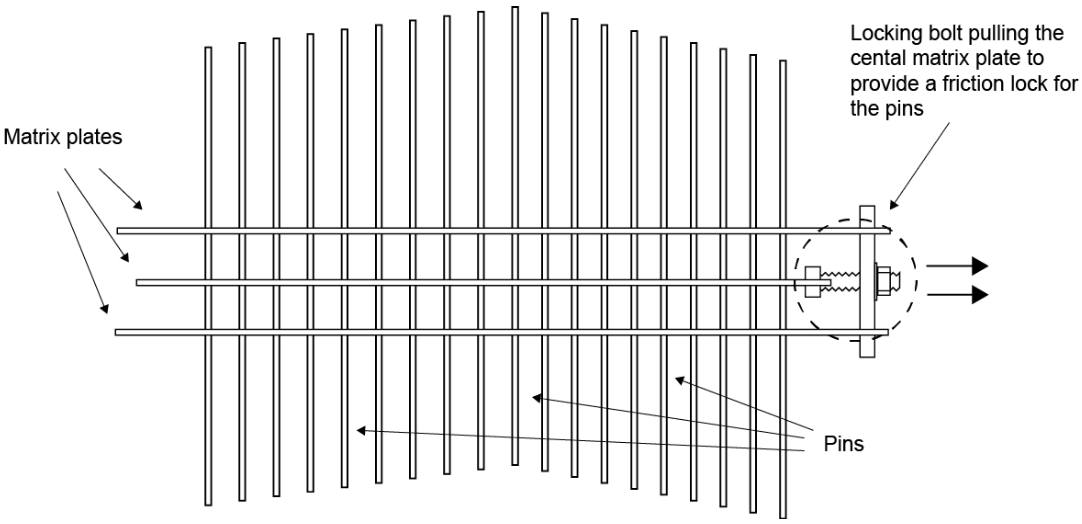


Fig. 35 The pin locking approach used in the second (large) glass RPT device.

In order to achieve the highest possible level of alignment of the holes the three matrix plates were stacked and bolted together and the holes were drilled with the university's in-house CNC milling machine (see Fig. 36). While assisted by CNC, the drilling of the matrix of holes in the large glass RPT tool still posed a significant challenge. This was partly due to the very large number of holes and partly to the very hard marine grade stainless steel used for the matrix plates. A high number of cobalt alloy drill bits were expended in the initial attempts and the successful completion of the task was only achieved when a specialist carbide drill bit was acquired. A customised jig also had to be constructed to enable the stacked matrix plates to clamped to the bed of the milling machine.

Fig. 36 The pin hole drilling process using Falmouth University's in-house CNC milling machine, photos: T. Jørgensen, 2012.

Following the drilling of the holes the rest of the construction was mainly concerned with joining the matrix plates with basic mass-produced standard parts such as nuts and bolts. These parts were acquired from local suppliers, all in marine grade stainless steel. In this regard it is relevant to highlight that the easy access to such parts was assisted by a sizable marine industry sector in the researcher's local area. The researcher considers the easy access to such components to have significantly aided the construction process of the RPT devices.

The final element to be added to the system was the pins. These were made from 4mm round bar (also in marine grade stainless steel), which were cut and ground into lengths of 300mm. The production of the pins marked the end of the main construction stage, however, further modifications and improvements to the tooling device were implemented in response to the on-going tests.

7.1.4 Initial Artistic Explorations

Initial creative explorations with the smaller circular glass RPT system had indicated a potential for using the characteristics of the moulding medium (sheet glass) as an integral part of the RPT production concept.

Through these tests the researcher had established a tacit knowledge of the various levels of fluidity the glass would have, which was dependent on a particular temperature. Through this developing knowledge of the material characteristics of the molten glass, it was found that shaping the pieces could be done by using only a few strategically positioned pins and leaving a particular level of fluidity in the molten glass to determine the shaping of the glass between the pins. This meant that only a few pins were needed to define the shape of a very large glass bowl.

This way of actively using the material characteristics of the moulding medium to inform the use of an RPT system through the use of few pins positioned in selected holes within a matrix, appears also to be novel in terms of the history of RPT. The contextual review revealed no record of RPT concepts based on such a selected pin positioning approach.

As previously stated, this part of the practice enquiry was, from the outset, intended to focus on the researcher's artistic exploration of the RPT concept. The use of the selected pin positioning approach to creating glass bowls (rather than through a full matrix of pins) also corresponded well to the researcher's aesthetic preferences. By only using few pins the fluidity of the semi molten glass could be highlighted and used as an integral part of the aesthetic of the pieces.

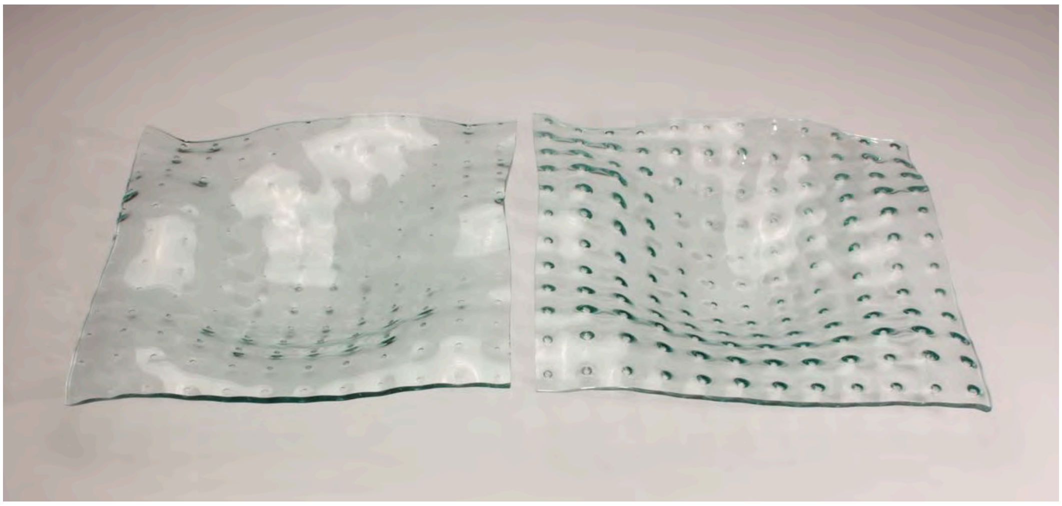


Fig. 37 Pre study experiments showing glass pieces (2010) created with a full matrix of pins, photo: T. Jørgensen, 2010.

Pre-study experiments using a full matrix of pins produced glass pieces, which had tightly nested indentations created from the pins in the RPT device. This evidence of the moulding process was further emphasised through the optical effects of the transparent glass, and resulted in an unattractive and *noisy* visual characteristic in the glass (see Fig. 37).

While the researcher's interest in the selected pin placement approach was predominately based on aesthetic decisions, the use of such a method was also beneficial in the practical use of the system as it significantly lessened the functional demands of the device. Such an approach meant that modest demands would be placed on the capability of the RPT device in general, and the pin locking aspect in particular. Early experiments with the RPT device had also indicated that the side of the glass that was facing the pins was generally more visually attractive, perhaps due to the positive *draping* of the glass between the pins. As a result, an approach was used where the glass bowls were created upside-down.

Fig. 38 RPT system removed from kiln with bowl still resting on pins, photo: T. Jørgensen, 2012.

This approach also enabled the researcher to position a number of pins to form points on which the piece would stand. Initially, six pins were used to create these points, but the number of pins to create the bowl's feet were reduced to just three, as this number would ensure a tripod position for the bowl to stand on without the risk of rocking (see Fig. 39).

The overall number of pins used in the selected pin spacing approach was initially quite large with up to 50 pins being employed. However, as experience was gained with the process, the number of pins was reduced through an iterative artistic exploration. In this creative investigation the researcher sought to create pieces that contained elements of *aesthetic drama*. After the production of each piece, an artistic evaluation was carried out and some of the pins would be repositioned in an iterative process to improve the expression of the pieces. During further experiments the number of the pins was reduced to let the material characteristics of the semi-molten glass *do more of the forming process*. After the creation of a considerable number of glass pieces, an optimum number of pins to achieve the desired aesthetic was established. The number of pins in this approach was clearly dependent on the overall size of the each individual glass piece. For the largest pieces produced (using glass disks of 590 to 615mm in diameter) an optimum number of pins ranged between 17-25 (including three pins to form the standing points). For the medium size pieces (using glass disks of 525 to 535mm in diameter) an optimal number of pins were established at a range of 11-15 pins.

Fig. 39 Image illustrating the tripod approach with the *Pin Bowl* feet (2012), photo: T. Jørgensen, 2013.

Several different sizes of glass bowls were explored with this approach, and while the basic aesthetic expression of the pieces produced could be described as similar, the capacity to refine the glass pieces through a constant repositioning of the pins was noted as a very useful feature of the RPT concept.

To the casual observer the appearance of the free-form aesthetic may seem random and uncontrolled, however, the aesthetic of glass pieces (particularly in the later iterations) was the result of a gradual refinement facilitated by the ability to reposition the pins in the RPT device to achieve a very specific artistic expression.

It should also be highlighted that the researcher produced in excess of 50 pieces that were deemed to be of a quality to submit for exhibitions or supplied to galleries as commercial products. But even after achieving a good number of high quality pieces, the researcher still undertook constant iterations of the forms, which inevitably lead to many pieces being discarded as unsuccessful on the basis of his aesthetic preferences.

Fig. 40 Iterations of *Pin Bowls* (2012-13) in the researcher’s studio. Many of these have been discarded due to the researcher’s artistic quality control, photo: T. Jørgen-sen, 2013.

7.1.5 Exploring the Role of the Moulding Medium

The role that the material characteristics of semi-molten sheet glass played in directing the creative approach with the RPT concept has already been discussed in the previous subsection. However, the glass medium also presented unexpected challenges that had to be addressed in order for this RPT concept to produce aesthetically successful pieces. The following section describes these issues and the unexpected problems the moulding medium (in this case sheet glass) can present to the innovation process.

Throughout this investigation 6mm thick lime-soda sheet glass was used. Such glass is used as standard windows glass, and also referred to as ‘float glass’, a term that refers to the fabrication method used to produce this kind of glass. It is a process in which the raw glass is melted in a giant crucible and continuously poured onto a bed of molten tin. The glass *floats* on the liquid tin and thereby achieves an extremely high level of flatness and clarity (Bricknell, 2010). Prior to the invention of float glass, sheet glass had to be manufactured by feeding the molten glass through rollers, sometimes employing a subsequent polishing stage if a very high level of clarity was needed. The development of the float glass method was a hugely significant innovation in glass production, both in terms of quality and efficiency (Bricknell, 2010).

Currently float glass is available in a standard clear colour (which actually has a slight green tint), as well as a number of stronger tinted colours, which are primarily intended as a solar control measure. Pilkington Optifloat™ float glass range was used (Nippon Sheet Glass Co., Ltd, 2015), which includes a range of blue, green, bronze and grey tints as well as the Optiwhite™ product, which is marketed as having a very low iron content, and therefore almost colourless. All these glass colours was explored in this study.

Float glass is a very useful raw material for glass slumping due to its low cost, consistent thicknesses and high clarity, but the material also has some drawbacks. One particular problem originates from the production method of floating the glass on molten tin. In this process the glass gets slightly contaminated with a tin residue on the side that is in contact with the molten metal. This contamination is not visible to naked eye, but it can have a significant effect when the glass is reheating in a slumping process. Here, tin particles on the glass surface often causes 'devitrification'. Devitrification is the formation of tiny crystals on the glass surface resulting in a white misty appearance. Cleaning the glass thoroughly before the slumping process can lessen the problem of devitrification, while variations in the temperature of the glass kiln can exacerbate the issue.

The problem with devitrification was far more persistent with the RPT tool than with other slumping moulds. This was probably due to the bulk of the stainless steel in the RPT tool causing heat differentials in the kiln. To remedy the issue, a number of cleaning methods and substances were tested. The researcher observed that the Heavy Duty Glass Cleaner from Bohle (Bohle Ltd., n.d.) would remedy the problem somewhat, but not entirely. While trying to identify why this cleaning fluid would have an effect, it was discovered that the fluid contained a small percentage of Hydrofluoric Acid. As this substance was known to have been used to etch glass, it was concluded that it was this particular ingredient in the cleaning agent that was having an effect. In order to achieve a better remedy for the problem the researcher attempted to source a compound with a higher concentration of Hydrofluoric Acid and found through Internet searches a product known as Pickling Paste intended for cleaning stainless steel welding joints, which also contained Hydrofluoric Acid. After acquiring samples of Pickling Paste, through testing it was established that the compound was highly effective in addressing the issue of devitrification.

Fig. 41 The glass cleaning process established by the researcher. The process starts by of identifying the tin side using a ‘tin scope’, followed by application of Pickling Paste, concluding with a polish with methylated spirits, photos: T. Jørgensen, 2014.

On this basis of this knowledge the researcher developed a particular cleaning sequence for the glass used in this investigation. In this sequence the tin side of the glass would be identified through the use of a tin detector using shortwave UV light. The Pickling Paste would be then be brushed in several directions on the side of the glass. The paste would be left to operate for up to 3-4 minutes and then rinsed off with water, followed by a final polish with methylated spirits. But even with this cleaning process, it was found that some very slight devitrification could still occur in the glass, which could be elevated by orienting the glass disk with the tin side facing up (and away) from the RPT mould. Finally, by using this combined approach the researcher achieved consistently good results with no evidence of devitrification in most glass types.

While the problem of the devitrification may seem somewhat peripheral to the core technical focus of the RPT concept, it was still critical to address this issue in order to achieve high quality artefacts, which could be exhibited and sold as commercial products. The problem with devitrification further illustrate that the material characteristics of the moulding medium can have a significant role in the development and practical use of an RPT concept.

The initial focus of this practice enquiry was primarily aimed at resolving the technical challenges of the RPT tooling apparatus, while the moulding medium was considered to be a far less significant aspect. Through reflections on this practice strand the researcher now recognises that the material characteristics of the moulding medium should be considered to a far higher degree and should be integrated closely within the process of innovating with new tooling methods.

7.1.6 Extending the Exploration of Aesthetic Possibilities

This subsection will describe the researcher's work in extending the creative exploration to include other aesthetical possibilities with the system. The text covers the rationale for undertaking this part of the enquiry and the creative development within this process. Apart from extending the creative exploration, this part of the enquiry also led to the development of a much-improved pin locking method, which is also described in detail.

While the researcher had been successful in developing an approach with the glass RPT system that facilitated the production of glass pieces with a fluid, 'free-form' aesthetic, the initial stage of the creative investigation also exposed significant limitations with the concept.

As previously highlighted, the aesthetics in the initial glass pieces were predominately the result of the researcher's aesthetic preferences in combination with the material characteristics of the sheet glass medium. While the first cycle of creative explorations resulted in the production of successful pieces (both artistically and commercially) it was found that attempts to create pieces with different aesthetic expressions were curtailed by the capabilities of the RPT system. Very early in the creative exploration issues with the friction based pin lock became evident. The process of applying lateral pressure needed to enable a good friction lock on the pins, which would, over time, result in the pins distorting significantly. The fluid aesthetics of the initial series of pieces was achieved with a relatively small number of pins and the pin distortion and therefore did not present serious issues in terms of achieving a secure lock for the pins. However, it was still evident that this locking approach was not a viable solution.

One of the objectives of the creative exploration with the glass RPT system was to investigate the versatility of the RPT concept, which in the context of this part of the study was identified as the ability to produce glass pieces with a range of very different artistic expressions. The production of such pieces would provide evidence for the RPT as a flexible and versatile production concept.

Initial attempts to improve on the locking mechanism by providing a *spring* element via the inclusion of a semi circle cut around each pin (illustrated in Fig. 33), was found to ineffective. Overall, it seemed that the friction lock concept was limited to working with only a few pins, and even with a small number of pins, still not particularly satisfactory solution. The limitations of the system meant that creative exploration was initially more limited in scope than anticipated as the problems with the locking mechanism curtailed the opportunity for exploring a much wider range of aesthetic expressions. The RPT concept's key advantage as a highly flexible production concept was, in this situation, largely constrained to provide an option for gradually refining the pieces. In this aspect, the RPT system did perform well and the system was also very successful in providing the capacity to produce a range of different sized pieces.

However, the limitations of the system, due to problems with the pin locking mechanism, remained a major issue in achieving the full benefits expected from the RPT concept. This meant that the creative exploration was severely curtailed by the system's inability to lock more than 30-40 pins. Throughout the creation of the initial bowl series, the researcher developed ideas for alternative artistic outputs with the system, in particular, ideas for pieces with a much more formal geometric aesthetic through the use of a high number of pins. However, to achieve such pieces it was clear that the pin locking mechanism needed to be improved significantly. From the outset, it was intended to cross-fertilise the knowledge from the two practice strands, and the issues concerning the locking mechanism was sought to be resolved through such knowledge cross-fertilisation.

The foam RPT system had by the time the pin locking problems emerged in the glass system, reached a good stage of development. This system had a successful locking mechanism based on a locking plate that was facilitated with springs, which meant that locking each individual pin was successful within a much wider range of contraction tolerances. Ways of transferring this concept to the glass RPT system were considered. However, it was concluded that a direct replication of this mechanism would be create significant risk of deformation when exposed to the temperatures needed in the glass forming process. Furthermore, the glass RPT system would require the concept to be scaled up significantly to a capacity capable of holding a total of up to 547 pins (the total number holes in the matrix plates). Equally, the square format employed in the foam system had to be translated into the circular format employed in the glass forming systems. Instead, the researcher sought to adopt a spring holding concept that was inspired by the foam system, but implemented via a simpler *individualised* pin lock, rather than foam system's *global* locking approach, which sought to lock all pins simultaneously via a central plate.

In order to establish a simple individual pin locking system a range of designs were carried out for small stainless steel collars that had an integrated spring mechanism. Just like the majority of the other components for the RPT device, these designs were fabricated via laser cutting. However, tests with these designs quickly exposed flaws with this approach too. The individualised pin collars would hold the pins well during the initial firing, however, the glass forming temperature would temper the stainless steel and the spring would lose its elasticity after just one, single firing. While it was possible to reposition the spring back to re-enable a good lock on the pins, this adjustment would have to be carried out on all collars after each firing and such an operation would clearly be very time consuming, rendering this approach non-viable.

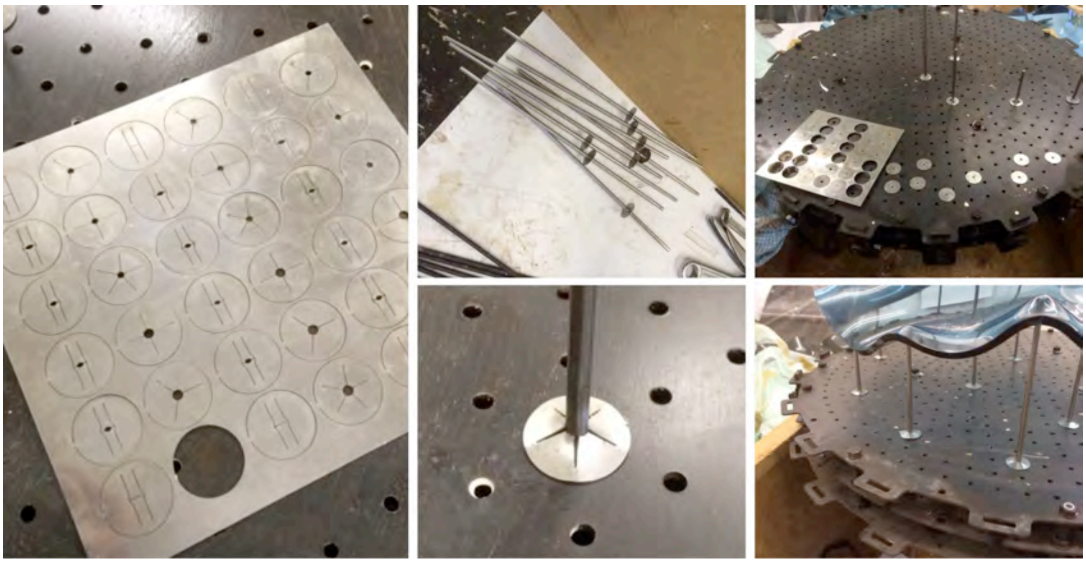


Fig. 42 The initial attempt of creating individualised pin holding brackets for the glass RPT system, photos: T. Jørgensen, 2014.

In order to establish an alternative locking approach, which was not dependent on the elasticity of the steel, the researcher sought to draw inspiration from other applications and sources. As an avid DIY'er, and in the search for a suitable locking concept, he drew inspiration from his knowledge in this field. A possible solution was identified from the principle employed in a typical mastic gun. Here, the piston drives out the mastic from the cartridge and is prevented from sliding back by a metal plate that is angled against the piston rod. This concept ensures a very good and reliable lock. While locking principles used with the mastic gun still employs a spring to insure that the locking plate is kept in full contact with the piston rod, the actual lock is provided by the angled plate and not the spring. As the glass RPT approach was dependent on gravity to force the glass into shape against the pins, the tooling device (unlike a mastic gun) would only ever be used in a horizontal orientation. This situation enabled a similar angled plate locking approach, but with gravity applying the force that would ensure that the plate was always in contact with the pin, in effect simulating the role that the spring has in the mastic gun principle. The researcher also identified other examples of the use of this locking principle, notably in the mechanism for holding up the lid of his glass slumping kiln.

Fig. 43 The inspiration for the researcher’s pin holding system: a standard mastic gun and mechanism for holding the researcher’s glass kiln lid. Photos: T. Jørgensen, 2014.

With this principle in mind, a holding bracket was created as a small circular disk with a 4.1mm diameter hole to accommodate the 4mm diameter pin. The design was developed by creating a bracket with a single angled leg which would ensure a pivoting action and thereby a locking action for the pins.

Fig. 44 The first prototype of the holding bracket developed by customising parts from a previous and unsuccessful bracket design. Photos: T. Jørgensen, 2014.

Initial tests with this design instantly indicated that this approach had very good potential for creating a successful pin lock. These tests showed that in using the brackets the pins could be easily arranged in position by pushing the pins from below the matrix plates. The trials also showed that the pins could be released in any given position with gravity, ensuring the holding bracket would provide an instant grip.This grip could easily be released by pushing the pin upwards, or if a lower position was needed, the holding bracket could be lifted in the opposite side from the angled leg, enabling the pin to drop freely.

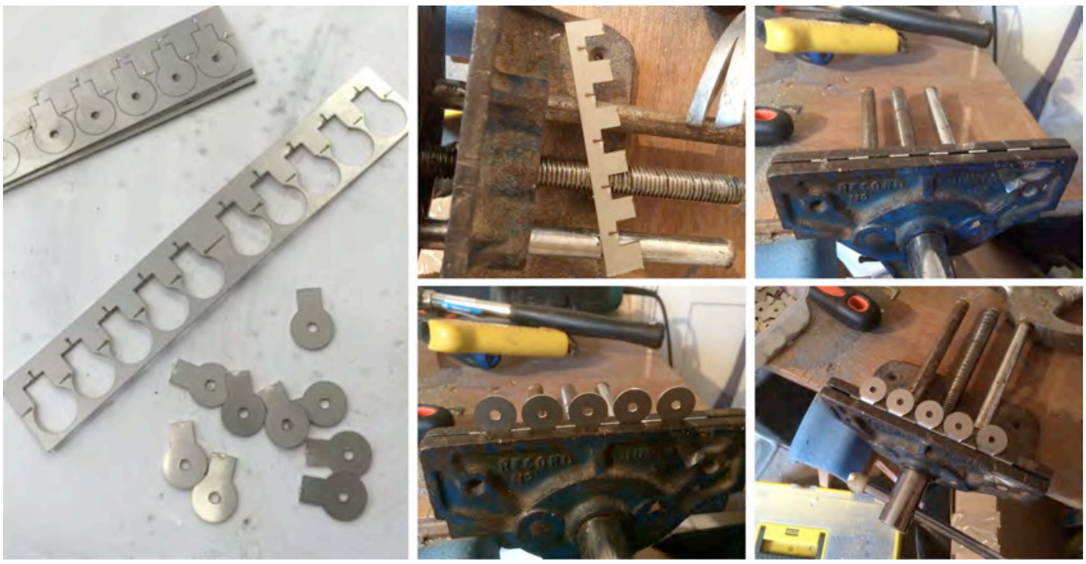


Fig. 45 Images illustrating the production of the holding bracket using a combination of high precession laser cutting and improvised jigs to bend the brackets accurately, photos: T. Jørgensen, 2014.

After initial tests with the holding bracket providing highly promising results, a full complement of brackets was produced. The only minor adjustment that was needed from the initial prototype design was an increase in the diameter of the central hole from 4.1mm to 4.2mm to accommodate oxidation of the stainless steel pins (caused by the glass fining temperatures). The production of the holding brackets was again done via laser cutting. The legs of the brackets were bent manually and the waste shape from the laser cutting process was used as an improvised jig to ensure accurate and consistent positioning of the bend. The pin-locking concept, now established, enabled the glass RPT system to be operated with any number of pins.

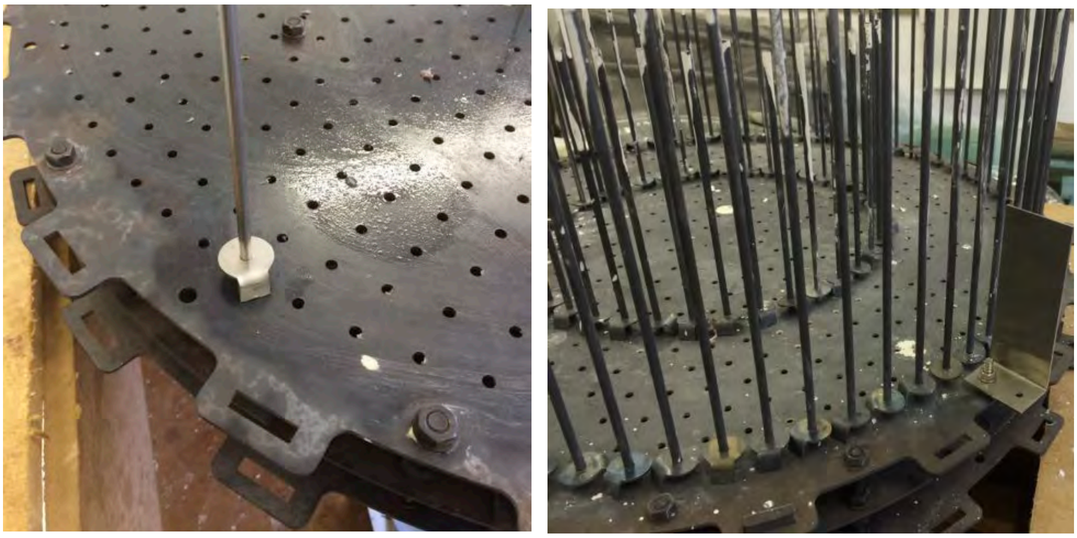


Fig. 46 The holding brackets in operation, photo: T. Jørgensen, 2014.

The system's capacity of holding a high number of pins could be combined with the researcher's interest in creating much more formal geometries in the aesthetic of the pieces. As a response, the researcher started to explore the possibility of placing the pins in concentric circles. These circles of pins could then be used as apertures through which the glass would sink into during the slumping process and thereby create bowl forms. This type of aperture slumping is well established among glass artists, but the process is generally only used with a single aperture. Such apertures are static and can only produce one particular diameter in the glass piece. In contrast, with the RPT approach developed in this study, the pins can be positioned to form a range of different diameters. The capacity of the large glass RPT device can provide 13 apertures that range from 50mm diameter to 480mm in diameter. Furthermore, unlike other aperture slumping approaches, the RPT tool presents the option for using a number of concentric apertures to create glass forms. The potential of using a number variable aperture diameters in combination with variation in the pin heights, presents an extremely broad range of artistic possibilities within this particular creative theme.

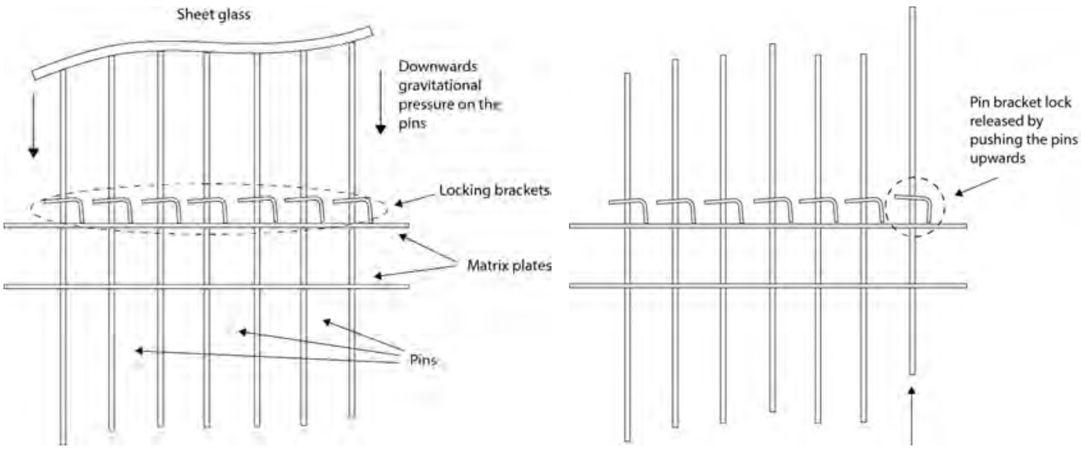


Fig. 47 Diagrams illustrating the principle and use of the ‘mastic gun’ locking bracket approach.

In contrast to the initial series of glass bowls, which were all created upside-down, this approach enabled the bowls to be created in the opposite (natural) orientation. In order to maintain a straight and level rim a stainless steel collar was integrated within the RPT system. Bowls produced with this approach have a natural, domed base, and due to this feature, the pieces from this series stabilise themselves into an equal level — balancing on the round base. The bowls will usually rest at a slight angle, which helps to emphasise the aesthetic of the pieces with orbits of concentric circles crated by pin marks from the moulding process.

Fig. 48 *Blue Orbit Bowl* (2014) by T. Jørgensen, part of the second stage of the creative exploration of the glass RPT system, photo: T. Jørgensen, 2014.

Throughout an artistic investigation, that resulted in the production of more than 20 pieces, the pin holding concept was found to be extremely reliable. The researcher tested pieces with up to 186 pins positioned in three concentric circles without any incidents of pin movement. In this regard the geometric aesthetics of these pieces provided a very useful visual feature in the testing process. Failure of any of the pin locking brackets would be very obvious as a missing or misaligned 'pin indentation' in the glass of the final piece would show.

Fig. 49 Method established to enable a quick positioning of the pins to a uniform height using a glass disk as a jig to set the pins against, photos: T. Jørgensen, 2014.

In summary, the aesthetics of this second series of glass pieces did not only provide evidence for the creative versatility of the glass RPT system, but was also an excellent testing ground for the reliability of the pin bracket design.

However, the capacity to use a much larger number of pins did, in turn, also present other challenges; particularly the process of having to set these to accurate, and level positions. Initially, the researcher tried to position the pins by setting each individual pin against a locked digital calliper, however, this method was found to be very time consuming.

An alternative method was devised in which only three to four widely spaced pins were set against the calliper. A flat glass disk would then be placed on these pins and the remaining pins (all initially positioned in lower position than that of the few pins set against the calliper) would then be pushed from below the matrix plates until resting against the glass disk. This pin setting approach ensured a very quick, but also accurate way of setting the pins to a consistent height within a particular orbit.

Fig. 50 The *Orbit* series of pieces being exhibited at the *Future Heritage* feature at the *Decorex* show, London, September 2014, photos: T. Jørgensen, 2014.

Driven by exhibition opportunities, the researcher undertook a creative exploration within the artistic approach, resulting in the creation of 15-20 pieces. This series of pieces was titled the *Orbit* series, with the first pieces launched in May 2014 at the *Collect* show at The Saatchi Gallery, London. Pieces from the *Orbit* series were subsequently shown at the *All Markers Now?* Conference at Falmouth University, July 2014, and also featured in exhibitions at The Decorex show in London and the Pushkin Gallery in Moscow — both exhibitions in September 2014. These exhibitions featured pieces from the first as well as the second series of creative investigations, thereby highlighting the capacity of the RPT concept for enabling a versatile and diverse creative output.

7.1.7 Discussion and Analysis of the Glass RPT Enquiry

As previously highlighted, this strand of practice-based research was intended to serve a number of purposes in the overall study. To guide this aspect, a number of specific objectives were identified, which were highlighted in the introduction text to this subsection. As well as directing the practical research these objectives also serve as a useful point for discussion and analysis of the results of this part of the study.

The objectives for this practice enquiry strand were:

- To explore tools and factors in the innovation process.
- To explore the creative potential of the RTP concept in the context of designer-maker practice.
- To investigate RPT in a real life production situation and to explore the commercial potential for artefacts created via the system.
- To cross-fertilize with the other practice strand of the study.
- To test the potential for achieving a range of different aesthetics with a single RPT tool.
- To test the durability of an RPT tool in a practical production situation.
- To explore the role of the moulding medium in an RPT concept.
- To provide a test bed for the development of a new digital research gathering and archiving method.
- To disseminate the research to both academic and non-academic audiences.

The following text will provide a critical analysis and reflections in response to each of these individual objectives.

- **To explore tools and factors in the innovation process**

One of the central contentions in this study is that the access to digital design and fabrication tools are increasing the opportunities for independent innovators to operate. Key parts of the innovation scenario in this practice strand provide support for this contention. The marine grade stainless steel, which is the most suitable material to use for a heat resistant glass moulding tool, is a very hard material which is difficult to machine. Without the access to high-grade digital fabrication tools it would have been highly unlikely that the glass RPT concept could have been developed.

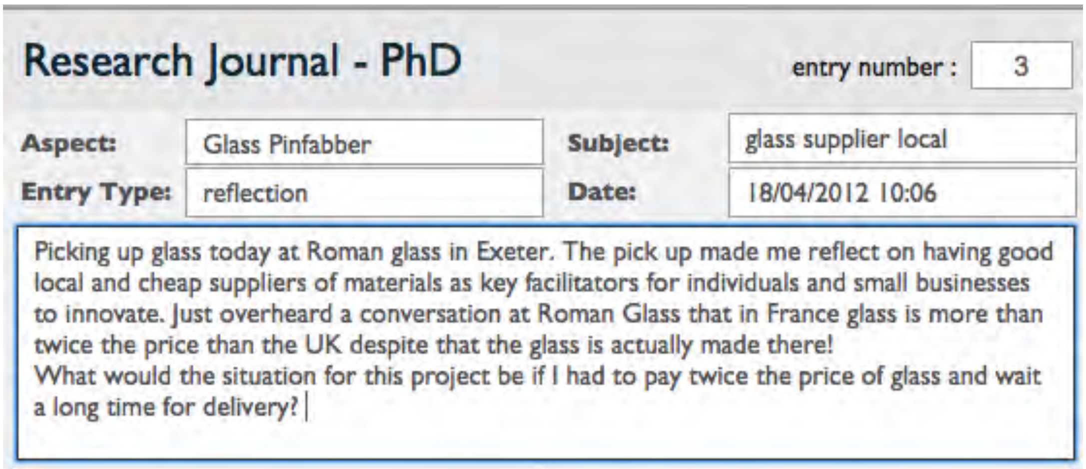
While the typical independent innovator is unlikely to personally own high-grade CNC equipment, such equipment can be accessed through bureaus, as illustrated by the researcher's use of a local laser cutting firm. Although the researcher did utilise the university CNC mill in the pin-hole drilling process, an external company could also have provided such a service.

The high degree of flexibility presented by CNC fabrication equipment means that individual innovators can get bespoke parts manufactured at low cost. Equally, CNC equipment presents the capacity for a very high level of fabrication accuracy and several aspects of this study have shown that achieving a high level of engineering accuracy are, at times, a very critical aspect in an innovation scenario. The wider notion of accuracy in innovation is also referenced in the contextual review, with Samuel Smiles' (1863) text from the birth of the industrial revolution specifically highlighting this issue.

In order to use digital fabrication services, it is also necessary to create the CAD files that such equipment operates from. Some fabrication bureaus do provide services for creating CAD files, but perhaps more frequently bureaus fabricate from files created by their customers. As discussed in the contextual review, the availability of computer programs to create such files is now widespread, with numerous powerful programs available as free and open source software. While the Rhino 3D CAD program that the researcher employed is not free or open source (but still relatively cheap), the powerful parametric Grasshopper module, which was also heavily used in this study, is currently entirely free to download.

The local environment in the shape of suppliers and subcontractors were also found to be significantly important in this practice strand. The construction of the RPT was entirely carried out using local suppliers, including the CNC laser-cutting firm as well as stockholders for all the other stainless steel parts.

Another example of this factor assisting independent innovation, concerns the supply of sheet glass. The researcher found no way of sourcing float glass from online suppliers, which meant that he had to rely on local firms as the only option. While local suppliers of float glass are widespread, the researcher's local stockholder, Roman Glass (Roman Glass, 2015), was found to be a particularly good retailer who was able to supply a very good range of glass at short notice and at prices that were generally half of other suppliers. Without this glass retailer the development of the glass RPT system would have been far more costly and lengthy, and the presence of this particular supplier was a very significant aid in the innovation scenario of the glass RPT systems. An entry into the research journal illustrates this significance of local suppliers (see Fig. 51).


Research Journal - PhD

entry number : 3

Aspect: Glass Pinfabber

Subject: glass supplier local

Entry Type: reflection

Date: 18/04/2012 10:06

Picking up glass today at Roman glass in Exeter. The pick up made me reflect on having good local and cheap suppliers of materials as key facilitators for individuals and small businesses to innovate. Just overheard a conversation at Roman Glass that in France glass is more than twice the price than the UK despite that the glass is actually made there!
What would the situation for this project be if I had to pay twice the price of glass and wait a long time for delivery?

Fig. 51 Entry from the researcher's IOS journal concerning the importance of local suppliers in the innovation scenario.

- **To explore the creative potential of the RTP concept in the context of designer-maker practice**

The initial creative explorations in this investigation lead to a number of discoveries, including the 'spaced pin approach'. Through the contextual review the researcher has been unable to identify other examples of a similar approach, and as such, the development of this particular approach with the RPT concept can be considered as an original contribution, both technically and artistically.

As previously highlighted, it was observations of the characteristic draping of the molten glass over the pins that mainly served as the inspiration for the creative response with the system. The first pieces that explored this approach (launched at the *Exempla Exhibition*, Munich, 2011) were arguably still somewhat *timid* in the artistic expression. However, through an iterative investigation the creative response was enhanced and developed. This situation could be characterised as a typical example of the researcher operating as a reflective practitioner in dialog with a situation, in what Schon would describe as responding to a situation's 'talk-back' (1983) — a notion which is discussed in the methodology chapter of this thesis.

Fig. 52 One of the first pieces created with the glass RPT system, photo: T. Jørgensen, 2010.

In addition to the spaced pin approach another innovative element, established in the initial stages of the investigation, was the approach of creating the glass bowls upside-down. This aspect could be seen as a somewhat basic intervention. However, it is the researcher's opinion that this particular approach was a very significant factor in developing the overall aesthetic concept, which enabled the creation of glass pieces with a very dynamic appearance. Reversing the effects of gravity in the aesthetics of the glass pieces from a concave to a convex expression, provided a particular richness of form.

Fig. 53 *Clear Pin Bowl* (2013) by T. Jørgensen, photo: T. Jørgensen, 2013.

The second stage in the artistic exploration with the glass RPT system, resulting in the *Orbit* series of pieces, was undertaken with a very clear objective of establishing an entirely different creative approach with the RPT system from the initial *Pin Bowl* series. While a much greater degree of geometric control was implemented in the Orbit series the researcher's material knowledge of the moulding medium still provided some of the basis for the creative concept for the pieces. The material characteristic of the molten glass will continue to play a large part in the on-going creative exploration, which the researcher intends to pursue beyond this study. It is also relevant to note that the pin-locking bracket developed for the second series of glass pieces, should enable many other creative investigations with the RPT system without being restricted by pin locking issues.

Fig. 54 *Grey Orbit Bowl* (2014) by T. Jørgensen, using three orbits of pins as the moulding apertures, photo: T. Jørgensen, 2014.

- **To explore the role of the moulding medium within an RPT concept**

Any moulding process could be argued to depend intrinsically on the material characteristic of the moulding medium. Take for example the process of bronze investment casting, which is dependent on the bronze alloy being heated to reach a liquid state and then solidify into a solid form in a refractory mould after being cooled. The glass RPT concept is equally dependant on the material characteristic of the molten glass disk being formed over the pins with the force of gravity affecting the shaping of the piece. While these observations may be somewhat obvious, it is perhaps still useful to reflect on the critical role the moulding medium plays in this successful application of this particular tooling concept. Articulated more accurately, it is the *innovator's* knowledge of, and expertise in using the moulding medium that, in this and many other cases, has facilitated the successful development of new innovative tooling processes.

With this in mind, it is perhaps justified to argue that it is beneficial to consider the medium and its material characteristic to a far greater degree when undertaking innovation in design and fabrication. It can be argued that currently the innovation in digital fabrication is predominately centred on applying materials to a technical principle (such as ALM), rather than developing technical principles on the basis of a particular material characteristic. The researcher readily concedes that, from the outset of this study, he was also guilty of this prevailing approach of focussing on a technical manufacturing principle before considering which medium this principle was going to be applied to. In contrast, the Fabbots project led by Martha Malé-Alemany can be highlighted as a particularly good example of experimentation with digital fabrication, which has a strong focus on the material characteristics of the production medium (Malé-Alemany, 2010).

Equally, it is also relevant to highlight that as well as being an intrinsic contributor to the form and aesthetic of the pieces, the material characteristic of molten sheet glass should also be considered as the single most significant *constraint* to the creative freedom with this production concept. For example, it was frequently found that certain pin positions would cause the glass disk to warp uncontrollably during the heating ramp resulting in the piece to fail entirely or produce a highly unattractive outcome with evidence of the glass sliding over pins and creating scratch marks.

Reflecting more broadly, it might be useful to return to the contextual review to reference the many innovators and researchers which, over the years, have been captivated by the allure of RPT with its description as a 'universal tool' or 'ideal tool' (Munro and Walczyk, 2007). The contextual review has shown that while a universal tooling system remains a captivating prospect, such a system is yet to be achieved. Based on the findings of this research the limitations of the RPT concept are equally likely to be caused by the material characteristics of the various moulding mediums rather than the operational technical details of the RPT device (such as those concerned with the setting and holding the pins). The previous statement should not be read as a view that considers the RPT concept of limited value if the somewhat utopian concept of *universal* tooling is not fully achieved. From this study there is clear evidence that the RPT has had a strong impact on the researcher's own practice and the researcher consider that the concept could also provide the basis for innovation in many other (creative) practices.

In conclusion, it is the researcher’s strong view that gaining benefits from the RPT concept can only be achieved if a high degree of consideration is given to the intended moulding medium. Furthermore, innovators exploring this concept have to be prepared to adapt both the tooling system and the output in response to material characteristics of the medium that they wish to process in such a tooling system.

- **To investigate RPT in a real life production situation and to explore the commercial potential for artefacts created via the system**

While the use of the glass RPT system in this study was essentially a creative explorative process, a substantial number of pieces (perhaps over a 100) were produced. Such a number of pieces provides a good basis for analysis of the RPT concept as part of a *real-life* production situation.

An advantageous aspect of a flexible tooling system is that any products produced can undergo continuous improvement in response to commercial feedback. The facility to gradually improve and refine a product during an actual commercial production was observed by the researcher as a very positive aspect.

Fig. 55 The two different sized glass RPT tools in the researcher's studio, photo: T. Jørgensen, 2012.

Equally, the ability to produce a wide range of sizes with the same tooling device was also observed as a very positive and useful feature. This means that production capacity is flexible and can therefore enable a response to changes in demand. Having just one tool also helps to minimise the storage needed for tools in a production environment. This aspect might be particularly relevant in the context of designer-maker practice where space resources might be limited. In relation to this issue, it was found that the larger glass RPT device was preferred in use for the production of all sizes of pieces rather than employing the smaller sized RPT device when producing smaller pieces.

One of the most obvious and significant aspects of the glass RPT system is the facility to produce objects that are not identical. In the market sector in which the pieces are currently sold this particular aspect has a tangible impact on the price. Both of the galleries, which currently stock the pieces, have expressed that individualised pieces will fetch higher prices than artefacts that are produced as a part of a series — for example, a limited edition of designs or series of prints. A price differential around 15 - 20% has been suggested as a likely impact in regard to this issue.

The initial Pin Bowl series has enjoyed a very good level of commercial success and the pieces are currently permanently stocked by two leading applied art galleries, The Wills Lane Gallery, St Ives and Vessel Gallery, London. Pieces from this series have also been acquired for a number of private and public collections, including the Crafts Council UK.

Currently, the pieces from the Pin Bowl series retails for £650 to £850, with the slightly larger Orbit bowls retailing for £1150 each. Of these prices, the researcher receives between 35 — 50% depending on the galleries' mark-up. Material cost for the glass ranges between £20 to £35 per bowl. The time spent on each piece is estimated to be 2 to 3 hours, with the majority of this time spent on polishing the edge of the glass disk (a task which has to be carried out prior to the firing). Overheads such as the researcher's studio rent, firing cost and failures rates should also be included in an overall calculation of the commercial and financial viability of the glass RPT system. But even without making a detailed calculation, it would appear evident that RPT concept within the context of the researcher's creative practice, is a viable commercial production system.

- **To test the durability of an RPT tool in a real-life production situation**

As a pretext to the analysis of this objective it is worth reiterating the somewhat challenging conditions that the glass RPT device had to endure in this particular production scenario. These conditions include repeated exposure to temperatures of 700-750ºC, the extensive use of refractory resist medium and a high exposure to general dust and production debris. It is also worth reiterating that while the production is clearly not on the scale of industrial manufacturing, over 100 firings are estimated to have been undertaken with the RPT devices. This level of use should be sufficient to provide a reasonable indication of the system's durability.

Within the context of this research, the main issue in terms of durability undoubtedly concerns the pin locking approach. The friction locking system initially employed would gradually distort the pins, creating increasing difficulties in operating the RPT device. However, this issue was addressed through the development of the pin locking bracket concept. The modified system was exposed to at least 20 firings with no indication of failures in the locking system and also no indication of the pin deforming through use. It can therefore be concluded that this pin holding system has completely resolved the pin locking issues with the glass RPT system.

Apart from the pin locking issues the researcher found the RPT devices to be remarkably resilient, with no noticeable distortion detectable in the main pin matrix plates. Despite the use of the marine grade stainless steel the surface of the device did, over time, become increasingly oxidised. Slight modifications to the system had to be implemented to deal with the effect of heat exposure, including increasing this size of the holes in the matrix plates as well as the pin holding brackets.

In summary, the overall assessment of the durability of the RPT system in this particular production situation is a positive one. While the researcher initially attempted to resolve operational issues with the system through the use of very high manufacturing tolerances, a useful general conclusion in relation to this objective is that RPT systems, which had to operate in harsh conditions (such as the glass forming environment), should be designed so as *not* to rely on construction concepts that depend on such high manufacturing tolerances. As a good example of such an approach the implementation of the pin holding brackets could again be highlighted as this solution appears to operate well within a wide margin of manufacturing tolerances.

- **To provide an analogue testing ground for the RPT concept**

While digital tools were employed extensively in the development of the glass RPT device the actual use of the system was entirely analogue. As previously outlined, the rationale for taking this approach was to include a practice strand which could progress rapidly with an investigation of the RPT principle in a more explorative way without the constraint of the technical challenges posed by the involvement of a CNC setting system. Another rationale for this approach was rooted in the researcher's interest in notions of combining new digital tools with manual skills in order to establish new models of creative practice (Jorgensen, 2007, 2005). In this approach, it can be argued that the creative and productive gains provided by emerging digital tools can be much enhanced if ways of making are developed that combine digital tools with analogue hand skills. The researcher argues that there is good potential for establishing entirely new hand skills in synergy with innovation in digital fabrication processes

In the case of the glass RPT system the use of analogue glass skills were central in producing the final artefacts. While some analogue processes could have been carried out by digital alternatives, such options did not present a more efficient, cheaper or creatively valuable option. An example in this regard is the possibility for getting the round glass disks cut with a CNC waterjet machine rather than the traditional circle glass-cutter. In this case, the use of CNC would have been a far more expensive option and would also have resulted in far longer production lead-times as the cutting of the disk would have involved subcontracting to an external firm.

Another obvious potential involvement of CNC technology in the glass RPT system is in the pin *setting* process. In the two current series of glass pieces, CNC pin setting is unlikely to have benefits in terms of production efficiency. However, it should be noted that the CNC pin setting for the glass RPT system could have some future potential. The researcher has ambitions for creating glass pieces that have very complex geometries created by a high number of pins, and for such pieces the use of CNC technologies could have advantages over a manual pin setting approach. Even with the potential involvement of CNC in the pin setting aspect, the production sequence, as a whole, is likely to still be heavily dependent on many stages being carried out by an operator using hand skills. This situation by no means should represent a failure in establishing a system which could be more automated, rather this could represent a vision for how new production systems could be developed to harness the human capacity for acquiring and executing highly developed manual skills. These are notions which also echo central ideas proposed by McCullough (1998).

- **To cross-fertilize with other practice strands of the study**

As previously highlighted, one of the very central aspects of this study is the notion of feeding the innovation process through input from other experiences and fields. The creative exploration of the RPT concept was, from the outset of the study, intended as a way of facilitating the study with a structure where separate practice investigations could cross-fertilise each other. In particular, it was the expectation that the glass RPT exploration would be an experimental *play-ground* from which technical knowledge could be drawn to feed innovation in the other practice strand of the study that was focused on the creation of a foam moulding system.

Although cross-fertilisation did happen between the two practice inquiries in terms of more general technical principles, it is difficult to identify specific examples of technical solutions which originated in the glass RPT investigation and were then later implemented in the foam RPT system. The reason why a clear transfer cannot be identified can potentially be attributed to a fundamental difference in the two moulding processes. The glass system is inherently a single-sided moulding process where gravity provides the force to mould the glass against the pins. In contrast, the foam system is a two-sided moulding approach with a very different shaping process. Equally, the moulding mediums have very different material characteristics. The glass is used in a sheet form and is a dense, heavy and semi-fluid solid medium — all characteristics that the slumping process depends on. In contrast, the foam is light, open-celled in a *bulk* form, with material characteristics as a highly elastic and compressible medium. These are all properties that the foam RPT system is completely reliant on. Furthermore, in use, the glass RPT system lent itself to the spaced pin approach, while the foam RPT system was operated with a full complement of pins in the matrix plates. Another obvious difference is the overall geometric shape of the two systems, with the glass RPT system being circular and the foam RPT system having a square format.

One of the shared technical requirements for the operation of two RPT systems was the need to establish a secure way of locking the pins. While solutions to this problem were attempted to be transferred from one practice strand to the other, a shared a technical solution was not found.

In conclusion, owing to the fundamental differences in the moulding mediums it was possible that the two systems were simply too disparate in nature to provide a transfer of technical solutions. However, it could be argued that having the two main practice elements technically and materially more closely aligned would not necessarily have ensured that a technical knowledge transfer would have happened. Theories (Pursell, 1994; Smith, 2005) concerning the value of outside influences in the innovation scenario do not indicate whether the value of such an influence is greater when it comes from a closely related source. In relation to this point it is worth reflecting on the concept for the locking brackets for the glass RPT system was sourced from the researcher's experiences in DIY and not the other RPT investigation.

Based on the finding from this practice investigation outside influences can be of significant value. However, a conclusion could be drawn from the experience with the structure of having two practice strands in this study that it is difficult to orchestrate a situation which will guarantee that specific *solutions* will transfer from one field of practice to another. However, the researcher still considers that the two practice enquiry strands provided valuable information to the overall study and that very useful knowledge was generated as a result of cross-fertilisation between these two practice strands.

Rather than transfer of specific technical solutions, the knowledge generated was far more significant on a wider conceptual level. This refers to an understanding of the shared issues in relation to the wider technical aspects, such as tolerances, wear/distortion, accuracy, rigidity, material characteristics and so on. In addition to facilitating a wider understanding of the RPT concept, generation of conceptual knowledge was also extended to more fundamental issues concerning tool use, tool-making, production issues and many of the other concepts that have been discussed in this section. It is of particular importance to note that the supplier network, design and development tools and prototyping approaches were all largely the same in the two practice strands.

- **To provide a test bed for the development of a new digital research gathering and archiving method**

As highlighted in the methodology chapter, the glass bowl investigation was instrumental in instigating the researcher's development of the IOS research journal templates that were primarily aimed at recording the investigation, but also used as a tool to facilitate the further development of the pieces and the RPT concept in general.

The initial attempts of data gathering through paper based forms and image libraries which lead up to the development of IOS database, have been covered in the methodology chapter. Equally, the value of this research tool in its various forms is also highlighted in several other parts in this thesis. However, it is still relevant to reiterate that it was the glass RPT investigation which drove the initial development of this tool. Apart from the features of the IOS template, it is important to highlight the importance of the iPhone's portability as a recording device in this investigation. The portability of powerful smart-phone technology meant that the facility to both record and retrieve data in the actual research environment was a very significant development tool in this study.

The use of the IOS database was subsequently employed for many other aspects of the study and the researcher has also utilised this approach in other research investigations, particularly one concerning the development of 3D printed glass moulds (Jorgensen and Matthias, 2013).

- **To Disseminate the research to both academic and non academic audiences**

Throughout this study the researcher extensively disseminated the outcome of the creative exploration via a number of exhibitions and shows including:

- *Decorex*, London, Sep 2014
- Moscow Design Museum, Sep 2014
- *All Makers Now?* Trelissick House, Truro, July 2014
- *Autonomatic At Making Futures*, Mount Edgcombe, Plymouth, Sep 2013
- *Critic's Secret*, The Mall Gallery, London, June 2013
- *Collect*, The Saatchi Gallery, London, May 2013
- *Best of British Showcase*, Crafts Council UK, Lancaster House, London, May 2013
- *Collect*, The Saatchi Gallery, London, May 2012
- *Tool at Hand*, Milwaukee Art Gallery, Milwaukee, Wisconsin, US, Dec 2011
- *Craft Code 011 – New ways of making*, The Wills Lane Gallery, St Ives, UK Sep 2011

Fig. 56 A series of *Pin Bowls* exhibited at the *Collect* show at the Saatchi Gallery, London 2012, photo: T. Jørgensen, 2012.

All these events enabled the researcher to present finished pieces from the creative exploration of the glass RPT system and thereby gain reactions from both academic and non-academic audiences. In some cases these events also enabled the researcher to present the context behind the study, which enhanced the opportunity for feedback and discourse.

Both *Craft Code 011* and *Tool at Hand* were good examples of exhibitions in which both the creative output as well as the wider research context was presented. The *Craft Code 011 – New ways of making* was a group show at the Wills Lane Gallery, St Ives, UK, which the researcher helped to organise. The show featured a number of the region's leading craft practitioners who explore the use of digital tools in their work. The exhibition booklet provided the opportunity to explain the notion of RPT and the wider rationale for the research.

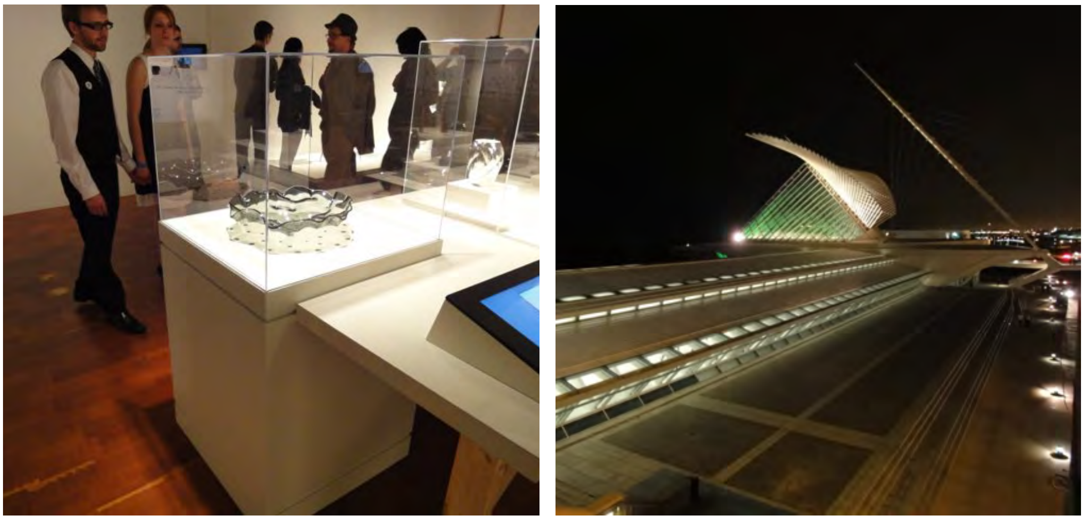


Fig. 57 *Pin Bowl* exhibited at *The Tool at Hand* exhibition, Milwaukee Art Museum, US, photo: T. Jørgensen, 2012.

Pieces from the Pin Bowl series were also featured in the *Tool at Hand* exhibition at the Milwaukee Art Museum, US, organised by the Chipstone Foundation (The Chipstone Foundation, n.d.) — a leading American foundation for the promotion of decorative arts scholarship. The exhibition was conceived by the foundation's then curator, Ethan Lesser, as an experimental project where a number of artists, designers and craft practitioners were challenged to create an object by using one single tool. The glass RPT device was a very appropriate fit with this concept, as the core concept of RPT is that a single moulding device can be used to create an infinite range of forms. In addition to the show, the researcher was also invited to participate in a think-tank at the Milwaukee Art Museum to debate ideas and concepts central to the show.

The think-tank was held in March 2012 and most of the exhibiting artists participated as well as leading scholars in the field of applied art, including: Glen Adamson, Ezra Shales, Jonathan Prown and Ethan Lesser. This event, in particular, enabled the researcher to engage in a discourse about wider ideas and concepts concerning notions of tools, tool creation and tool use — all concepts with key relevance to subject of this study.

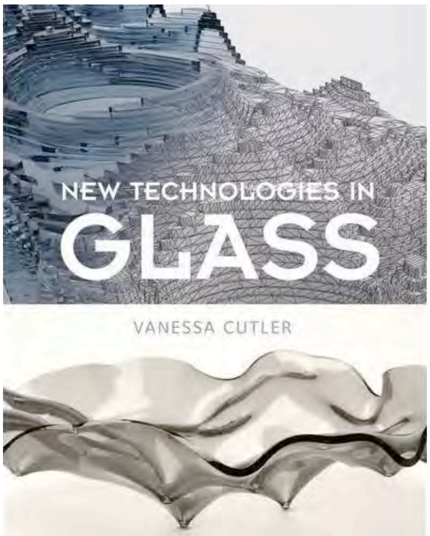
In addition to the Milwaukee Art Museum, the exhibition toured key American venues over a period of two years with exhibition venues including: Philadelphia Art Alliance, The Houston Center of Contemporary Craft and the Museum of Contemporary Craft, Portland, OR.

As a part of the *Tool at Hand* project each artist or designer was asked to record a short movie illustrating the making process of the piece. This movie was shown on a monitor next to each piece within the exhibition to provide context of each artefact. These movies are now available on permanent site established by the Chipstone Foundation (Indianapolis Museum of Art, 2012).

Fig. 58 The *Tool at Hand* think tank, Chipstone House, Fox Point, Wisconsin, US, March 2012, photos: T. Jørgensen, 2012.

In addition to dissemination through the exhibitions, images of the glass pieces were also featured in a number of publications including, *London Evening Standard, Crafts Magazine, American Crafts* and an image was also used to illustrate the cover of a book, *New Technologies in Glass* (Cutler, 2012).

From the considerable list of exhibitions and press coverage this objective of the investigation must be considered to be fully met. It could be argued that the dissemination has predominately focused on non-academic contexts, such as exhibitions and shows, but such dissemination has nonetheless lead to academic discourse and interaction, as the Chipstone example illustrates.



IDEAS

reconfigurable glass tool

Tavs Jorgensen
Grey Pin Bowl, 2011
grey tinted float glass
5.5 x 18.1 in. dia.

different from the ordinary relationship between people and things. In the 18th century, people often had their portraits taken with their tools. And tools

together thousands of small wooden dowels to make his *Dowel Bowl*.

Still other artists attempted to remake their typical work

a piece of found silver – a spoon from the 19th century. He covered the silver in lead and heated it in the oven. The lead acted as a corroding agent and literally

Fig. 59 Examples of the coverage of the glass RPT project in books and press.

7.2 The Development of the Foam RPT System

The following subsections will cover the development of the various aspects and elements of the investigation into the development of the foam RPT system The initial explorations in establishing the core foam moulding principle are described first. Further subsections then follow covering the development of various aspects of the system, such as core RPT units, supporting mechanical operation, pin tip design and the construction of the CNC elements. A subsection covering a collaborative CNC building workshop then intersects descriptions of developments in the RPT system, as this workshop provided the basis for developing the CNC aspect of the system.

It is relevant to note that the development process of this system (just like the glass investigation) has been rigorously recorded and this chapter includes a substantial amount of description of the technical details from the development process. These are, in part, provided to provide other practitioners who wish to explore the RPT concept with useful technical information established as a result of this study. However, details of the development process are also included as evidence to build a wider argument as the researcher considers that when solving problems in regards to small details that innovation can be practically and realistically demonstrated. Reflections on the development process of the RPT system in this practice strand are provided within the description of this process, with a concluding discussion provided in subsection 7.2.9.

In order to assess the innovation potential of the foam RPT concept, extensive testing was carried out on the system. These were structured in two key stages with a number of objectives defined for each of these testing stages. The practice enquiry chapter concludes with details and results of these tests.

7.2.1 Establishing the Core Moulding Concept

The initial framing of the concept for this strand of the practice enquiry was developed through fieldwork and reviewing literature. An early idea was to explore the RTP concept to make a system for ply moulding, but fieldwork in the shape of visits to furniture companies (Tandem Design, Plymouth and the Duriflex factory in Thailand) cast doubt over the viability of such an application. This was mainly due to the large amount of pressure needed for ply moulding and the resulting robustness required for the tool employed.

Fig. 60 Examples of ply moulding tools (Tandem Design, Plymouth and Duriflex, Thailand). Examples gathered from the researcher's scoping and fieldwork activities, photos: T. Jørgensen, 2010-11.

A number of discussions with the study's main industry partner, MARK Product, were undertaken to identify alternative applications for the RPT concept, particularly in relation to MARK Product's business model. A potential application was initially identified in relation to the manufacturing process of one of the company's existing products, the *Net Chair*, designed by Sam Johnston (MARK Product, n.d.). The individual elements of this chair are manufactured by CNC wire bending, which are then welded together to create a complete piece of furniture. It was proposed that the RPT moulding concept was used for the creation of a jig to hold the wires in position during the welding process. However, this potential application was also discarded due to size constraints, resolution issues and general practicalities. Instead, the notion of using the RPT concept as a method of shaping upholstery foam started to emerge. The idea was to use a manufacturing principle that is known from the process for creating the characteristic textured surface in acoustic insulation foam (see Fig. 61).

In order to manufacture this texture a slab of upholstery foam is rolled through a set of textured rollers that compresses the foam. Immediately, as the foam emerges from the rollers, a band knife cuts through the centre of the foam. As the foam is still in a state of compression when it is being cut, the foam is shaped by the texture on the rollers and as the foam springs back from this compression the three-dimensional texture is revealed.

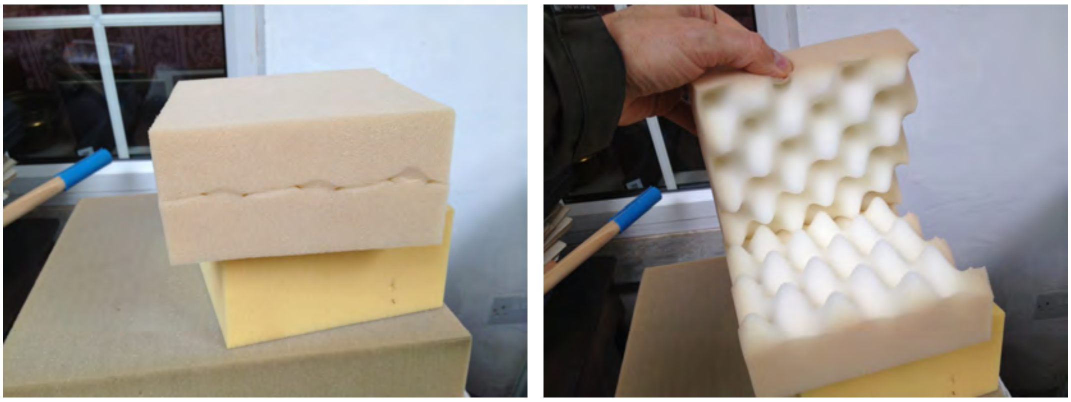


Fig. 61 Example of acoustic foam, the dimpled surface is achieved by cutting the foam while it is being compressed between textured rollers, photo: T. Jørgensen, 2012.

The concept of shaping upholstery foam in this way was thought to be a very promising application to explore with the RPT concept, particularly as the potential demands on the tooling device was likely to be relatively modest. The resolution was also deemed to be a less onerous issue as it was expected that the nature of the furniture form would carry out a degree of smoothing.

Later informal interviews with a local furniture foam supplier (Cook, 2014) indicated that this manufacturing concept had also been employed in other applications apart from creating acoustic foam. The researcher learned that the concept had also been used by a large mattress firm to shape cushions into certain shapes. However, all of the known examples of this manufacturing concept involved the use of static moulds (or rollers) and there was no indication from either the literature review or further scoping activities that the use of reconfigurable tooling devices having ever been used in connection with this particular process. Therefore, this application appeared to present an ideal opportunity for exploring the RPT concept in a new innovation scenario.

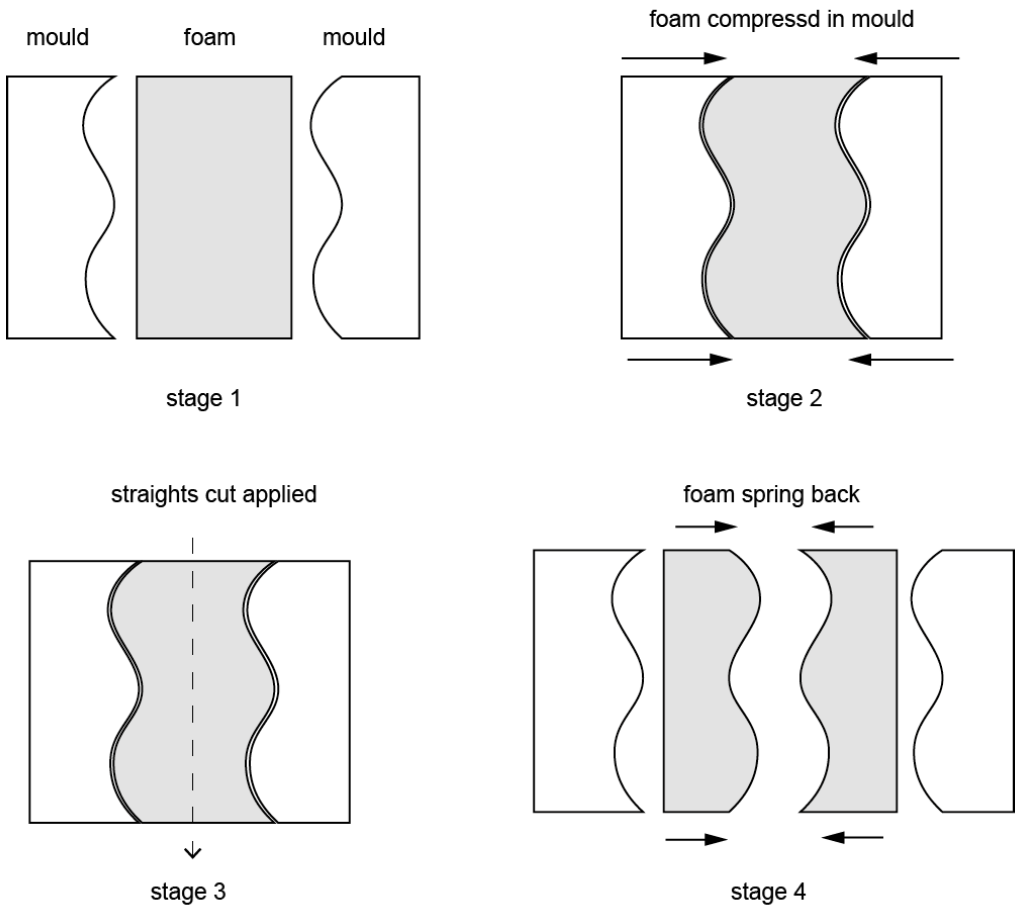


Fig. 62 Diagram illustrating the various stages in the foam moulding principle.

7.2.2 Early Concept Development and Prototyping Activities

After the decision to explore the RPT concept as a flexible moulding device for upholstery foam, a series of initial prototypes were carried out. These initial experiments were undertaken with a prototyping approach described by Schrage (1999) as 'quick and dirty'. The aim was to quickly establish the viability of the concept by undertaking tests with readily to-hand materials and equipment. A crude RPT device was constructed by cutting lengths of aluminium box section extrusions (20 x 20mm) to make a single RPT unit using a *closely coupled pin principle* (see **Error! Reference source not found.**). As a locking device, a primitive clamp was constructed from the same aluminium profile and generic plastic stoppers were applied to close the ends of the hollow aluminium extrusions. A wooden frame and plunger was also constructed in order to push the foam against the pin unit, as illustrated in Fig. 63. A standard electric bread knife with an oscillating action was used as the cutting device. Samples of upholstery foam were acquired from a local supplier to carry out initial trials.

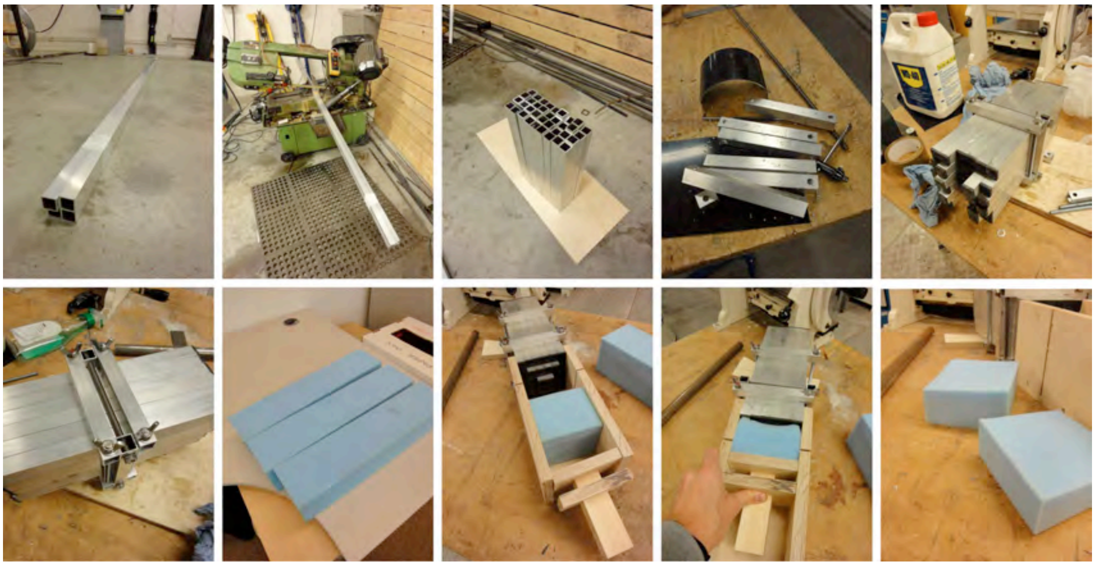


Fig. 63 The first round of prototyping exploring the RPT foam moulding concept, photos: T. Jørgensen, 2011.

The initial experiments with this set up provided only a limited success. Despite applying considerable pressure while cutting the foam only very minimal shaping was evident in the foam. The cause for this lack of shaping was thought to stem from the use of a flat surface (wooden plunger) to compress the foam against a single pin unit. Cutting the initial RPT unit in half facilitated further experiments with two pin units with opposing matched shapes. Experiments with this set-up proved much more promising and a second series of experiments with foam cutting were undertaken.

Although the set-up for these experiments was still very crude they provided sufficient indications that the core concept was indeed viable. By compressing the foam between two RPT units, with matched shapes, a very considerable amount of shaping in the cut foam blocks could be achieved when applying a straight cut in the compressed foam positioned approximately equally between the two pin units (see Fig. 64).

The objective for this series of experiments was to establish a proof of concept with quick prototyping with materials and equipment readily to hand. To further highlight the nature of this approach, several parts of the system was acquired from the researcher's kitchen such as an Aerolatte™ stand and breadknife. As previously highlighted, this approach of using parts and equipment appropriated from other intended uses to enable rapid prototyping was a based on a decision to employ development methodologies that are typical in the Hacker and Maker Movement communities.

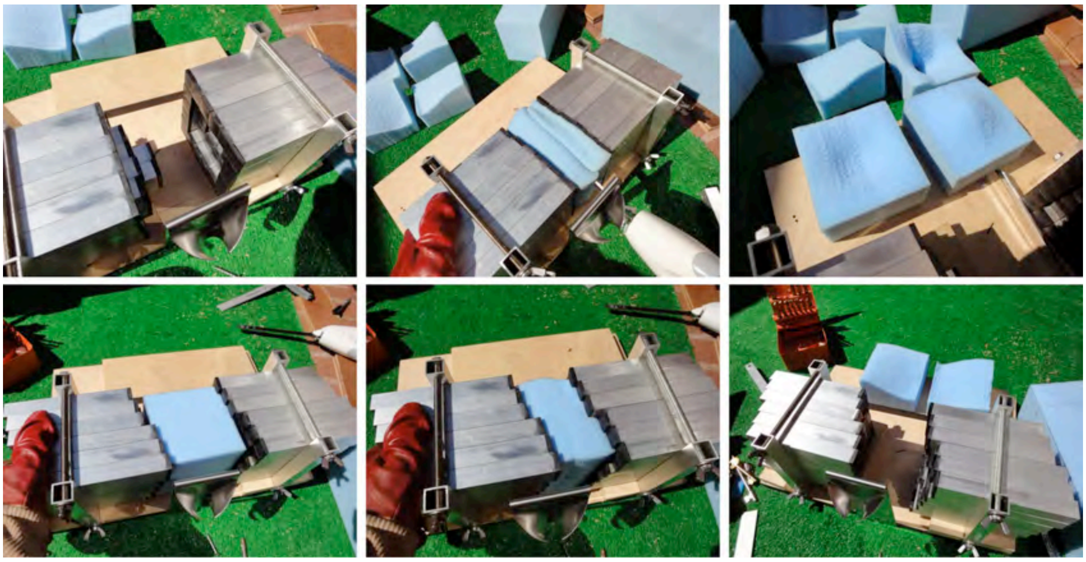


Fig. 64 Testing the RPT foam concept with opposing sides of tool, photo: T. Jørgensen, 2011.

With a proof of concept established through the ‘quick and dirty’ sessions of prototyping, further development of the core concept now had to be undertaken. Again, physical prototyping (rather than theoretical planning) was used in this developmental process. In this prototyping process card and foamboard was used to propose the shape and functionality of an operational foam RPT system.

The session established a concept for a system based on a controlled linear operation of the two opposing pin units. A concept was developed based on the pin units being located on frames fixed on ‘sledges’ that could be moved back and forth with a central rail guiding the movement. This principle was expressed as a profile located on the base of sledges and having a corresponding slot in the guide rail (see Fig. 65). These sledges were to carry detachable pin units located in slots in the frames.

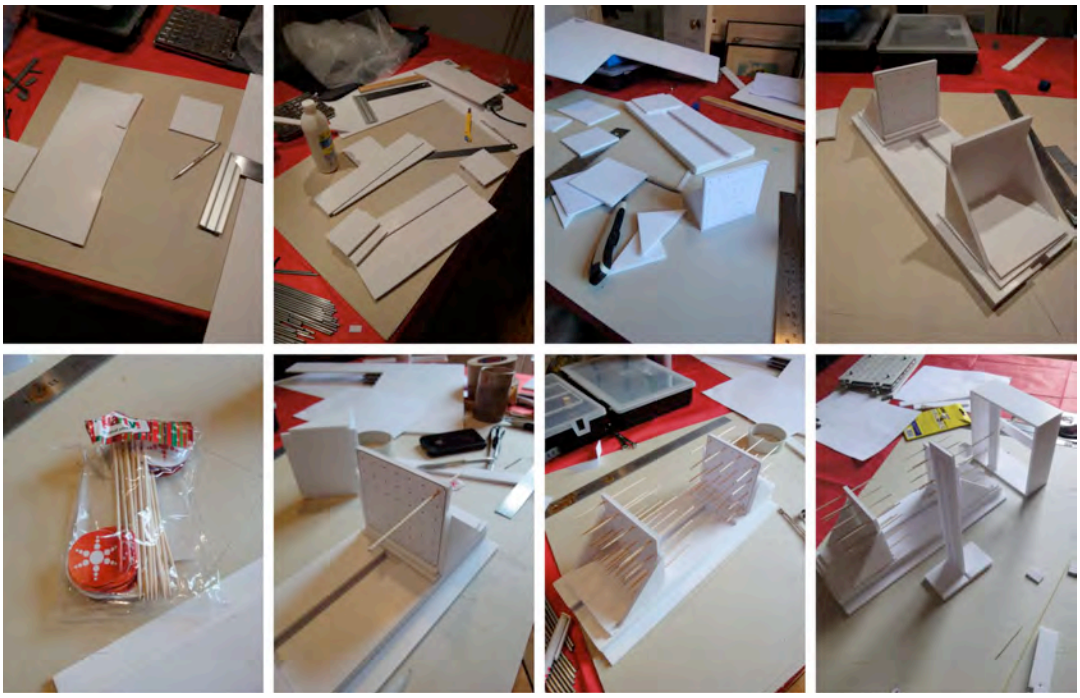


Fig. 65 Foam-board prototyping enabling further development of the concept of the foam RPT system, photos: T. Jørgensen, 2011.

A key objective in this prototyping session was to establish a way to cut through the foam positioned between the opposing pin units, particularly as any slot to facilitate a blade to operate between the pin units would most likely compromise the structural integrity of the system, especially as the pressure to compress the foam had to be maintained during the cutting stage.

Through explorative play with the foamboard a simple solution was established where the whole unit would pivot on a hinge fixed on the side of the rail thereby allowing a cut to be made by either a specialist foam cutter or by a standard bandsaw machine with a bandknife blade (see Fig. 66). The researcher believes that discovering the solution for this problem can be directly attributed to the particular prototyping process of interactive play with the card and foamboard models.

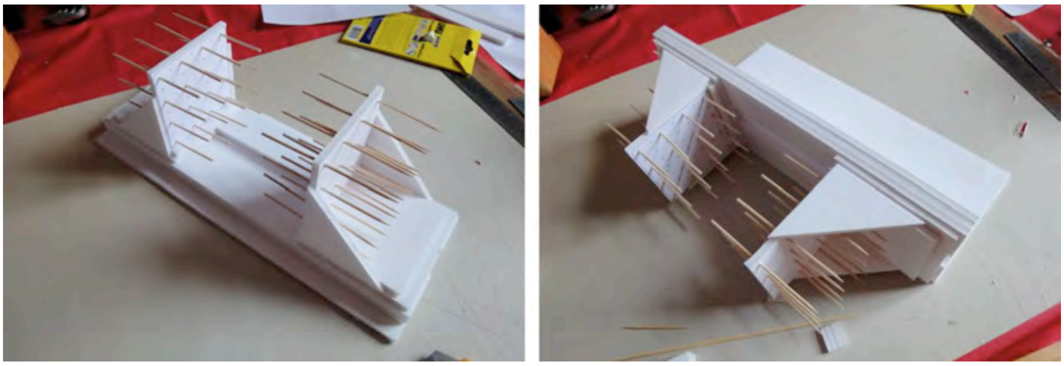


Fig. 66 The tilt action (discovered though paper foam prototyping) to enable the use of a band blade to cut the foam in RPT system, photos: T. Jørgensen, 2011.

It is worth noting that the overall layout of the RPT system established during this prototyping session remained fairly consistent during the subsequent construction of the functional RPT system.

The development of a functional foam RPT system was initiated shortly after the foamboard concept prototyping session. This system was intended to be a small but still fully functional system on which further testing could be undertaken.

7.2.3 The Development of the Core RPT Unit

While the basic concept with the rail and sledge construction remained the same throughout this stage of the system development, a significant change in the principle for the core RPT unit was taken prior to the construction of a functional system. Initial explorations of using the RPT principle with the foam moulding concept (illustrated in Fig. 63 and Fig. 64) had employed a close coupled matrix RPT approach. However, with the relatively modest pressure needed for the foam moulding application it was decided to change from the use of a close coupled matrix of pins to a system based on an 'equally spaced' approach. Both of these approaches are discussed in detail by Munro and Walczyk (2007) and illustrated in Fig. 9.

This decision was also based on results from the investigation with the RPT system for forming glass bowls, which by now was already well progressed. Based on experiences with the glass system it was judged that an RPT system based on an equally spaced matrix of pins would present an easier prospect of setting equally spaced pins via CNC. Experiments with the glass forming system had also identified that establishing a secure lock for the pins (once in position) was one of the main challenges with the RPT concept. This is a challenge that has been shared by many other researchers involved with the RPT concepts (as highlighted in the contextual review).

As previously described, the initial pin locking mechanism for the glass RPT systems was based on a very simple RPT set-up consisting of three matrix plates bolted together. The lock for the pins in these systems were provided by bolts applying lateral pressure to push the middle plate to fix pins in position via a simple friction lock principle. However, through the use of this system significant problems of this approach were exposed. It was found that such an approach required very high engineering tolerances. And while high manufacturing tolerances could be achieved through the use of CNC laser cutting to fabricated the matrix plates, the wear and tear through the use of the glass RPT systems quickly degraded initial high manufacturing tolerances. It is relevant to highlight that the glass RPT investigation provided a very good testing ground to explore generic issues with the durability of the RPT concept. Without this severe testing situation reaching such findings and insights may have taken much longer to emerge.

Experimentation within the glass RPT investigation was instigated to find ways of establishing a reliable and durable locking system. The researcher initially considered that adding an element of flexibility within the friction lock concept might enable the principle to work. This approach was implemented through designing a middle plate which had a semicircle cut near each of the pin holes. The expectation was that this cut would facilitate a level of flexibility in the matrix plate and therefore enable the friction lock to work, effectively adding a spring element to each individual pin hole. Although, through testing this approach was found to be largely ineffectual. The notion of incorporating a spring within the locking system was still deemed to have potential. Apart from lessening the manufacturing tolerances required for a successful locking device, the idea was also partly driven by observations with the early practical experiments with the foam RPT concept. These tests indicated problems with the foam sliding off parts of the pin units during the process of being compressed between unit before, and during cutting. The researcher considered that a locking system which incorporated springs could enable the pins to be moved in one direction while holding firm against pressure in the opposite direction. With such a system the pins could potentially be set while the foam was locked in low compression, potentially preventing the foam from being misaligned when a full compression level was applied.

In order to investigate the idea for a pin locking matrix plate that were enhanced by springs, another round of practical prototyping was initiated.

The facility to get highly accurate bespoke parts fabricated by local laser cutting companies had already been shown to be a key enabler in the process of creating the glass RPT systems. Experiences with this way of sourcing bespoke parts were very influential in guiding the design of the RPT foam tool. In particular, the design of the foam system was to a high degree guided by creating a construction that could be created by components that could be CNC laser cut. These components were mostly developed through rough concept development using hand sketches and paper folding. These initial designs were then further developed using the Rhino 3D CAD software and printed out on paper (using standard inkjet printer). During several iterations of this prototyping process the designs were further refined in preparation for fabrication in stainless steel.

Fig. 67 Developing the spring enhanced pin locking plates with integrated lugs for pull-push locking mechanism. Explorations all done via paper prototyping with a view of having these fabricated in sheet metal via CNC laser cutting, photos: T. Jørgensen, 2011.

The facility to use affordable and powerful CAD tools and to integrate these with analogue prototyping processes was noted by the researcher as being a very significant facilitator in this innovation scenario. The researcher considers that the availability of free or low cost CAD drawing packages in general were a very significant factor in facilitating independent innovation. Such CAD packages are capable of generating digital data that can be used both in the design and development process and then exported more or less seamlessly to external fabricators. As highlighted in the contextual review there are a large number of open source and free CAD programs available for independent innovators. The researcher extensively used a free beta version of the Rhino program for the Mac OS platform. A well documented example of other independent innovators use of this CAD program includes the ‘Glif’ iPhone holder (Provost and Gerhardt, 2010).

Through this prototyping process the researcher developed a design for a central locking plate that incorporated small flaps that could serve as a locking spring for each individual pin. Consequently, this middle plate had to be fabricated in a thin plate to facilitate a good level of flexibility in the springs. An integrated *fix point* for the bolt to facilitate the engagement and disengagement of the entire locking plate was also incorporated in the design, with a couple of design variations of this element being developed. These parts were designed to be made from flat patterns laser cut in the steel plate and proposed to be folded into a complete *fix point* or bracket (see Fig. 68).

After several design iterations using the prototype tools and methods outlined above, the designs for the foam RPT system parts were finally considered to be sufficiently developed to be fabricated via CNC laser cutting by a local company, Luffman Engineering, Tiverton.

At the time of writing, the *Yell.com* site lists 63 laser-cutting firms based in the South West of England, which illustrate the widespread availability of such a service. The typical turnaround time from submitting a drawing to fabrication is five to ten working days. Furthermore, the accuracy of laser cut metal parts is generally very high, with tolerances of less than 0.01mm. The eight stainless steel parts supplied to construct the initial foam RPT prototype cost £94.14, with the parts supplied within five working days. This situation suggests that an environment now exists where innovators can design and submit bespoke parts to be fabricated highly accurately with very quick turnaround times. The researcher argues that this constitutes a very fertile environment for independent innovation.

After the parts had been supplied, the design for the pin spring locks and brackets for the fix points underwent some early feasibility tests. These initial tests showed that this middle plate (fabricated in 0.5mm stainless steel plate) was not rigid enough to enable a consistent engagement and disengagement of the springs.

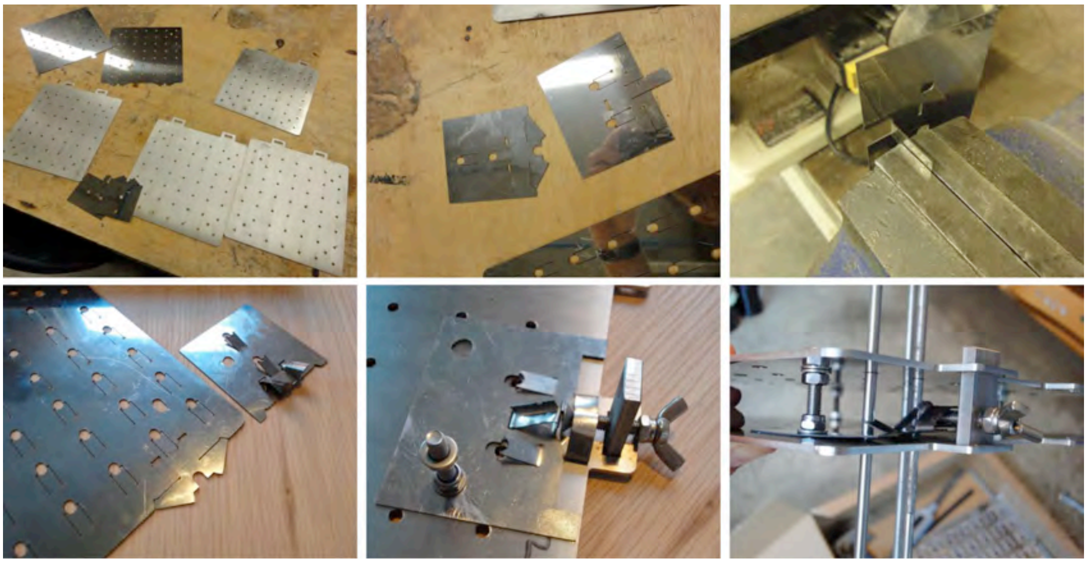


Fig. 68 The initial designs for a fix point bracket from folded metal plate. Designs developed from the initial paper prototypes as illustrated in Fig. 67, photos: T. Jørgensen, 2011.

In an effort to resolve this issue a pair of supporting panels was fabricated (laser cut in 3mm acrylic) to sandwich the metal plate with the individual spring locks between these acrylic panels. The supporting panels were designed with cut-out pockets to facilitate the springs operating freely. The initial designs for the bracket fix points (using the folded metal approach) were also found to have insufficient strength and a more robust fix point (in the shape of an integrated slot) was also developed as part of the design of the supporting acrylic panels.

These early alterations and improvements of the system were informed by on-going experiments and mini trials, all prior to the more formal testing of the system. To ensure more accurate feedback from these experiments a full complement of pins (98) were produced and employed at a relatively early stage.

The pins were produced from 4mm stainless steel round bar, which were supplied in three-meter lengths by a local metal stockholder. The only real challenge in the production of the pins was to ensure a high level of consistency in the length of the pins (200mm). A high level of consistency was required to be able to set shapes accurately from the data of the surfaces designed in the 3D software. Only a high level of consistency in the pins' length would ensure accuracy in testing results for the overall concept. In order to achieve this high level of consistency and accuracy a jig was constructed which could facilitate batches of pins that could be ground with a linishing machine.

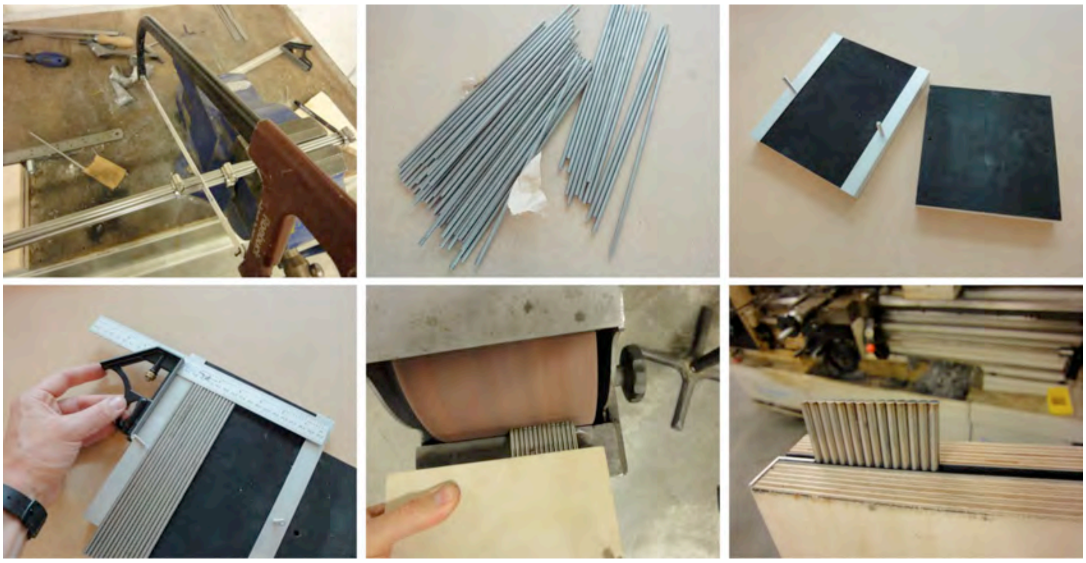


Fig. 69 The production of the pins aided by a jig made by the researcher for holding the pins while grinding them to equal lengths, photos: T. Jørgensen, 2011.

After the production of the pins, the completed RPT units with a full set of pins could undergo pre-tests to identify other potential issues that needed to be resolved prior to the system undergoing a formal testing regime. These pre-tests showed that even with the supporting acrylic plates the central locking plate was still not rigid enough overall to secure equal pressure on all of the individual pins. In response, a further set of supporting plates were fabricated in 3mm thick aluminium plate (a material that is significantly stiffer than clear acrylic). These supporting plates could potentially also have been fabricated via laser cutting, but due to expediency these were constructed using Falmouth University's in-house CNC milling machine.

The various construction iterations of the RPT device were greatly aided by versatility and portability of the digital design data. This data was initially developed though the process of designing the prototypes in paper, then subsequently used for files submitted to the laser cutting firm, then further edited and used for the development of the acrylic plates, and then finally utilised to cut the aluminium supporting plates via CNC milling.

Fig. 70 The development of the supporting panels for the central locking plate, initially using laser cut acrylic (top series of images) and subsequently CNC milled in 3mm aluminium (illustrated in the lower series of images), photos: T. Jørgensen, 2011.

Tests with the middle locking plate, stiffened by the supporting aluminium panels, finally indicated a good and reliable locking mechanism was close to being established.

While undertaking the contextual review concerning the history of the RPT concept the researcher has been unable to identify other examples of this particular spring enhanced locking mechanism, which allows the pins to be pushed in one direction while locking firmly in the other. Consequently this should be considered an original technical knowledge contribution.

7.2.4 The Development of the Supporting Mechanical Operation

Alongside the development of the pin units, work concerning the construction of the rail and sledge details were also undertaken. These details were critical aspects of the whole system as this set-up would enable the pin units to be operated consistently and securely.

As previously described the basic principle for the construction was established in the foamboard prototyping session but this concept had to be translated into a functional format. Birch plywood was chosen as a suitable material to use for the construction of these elements, partly due to researcher's access to a supply of plywood offcuts and also the ease of shaping this material to the desired proportions.

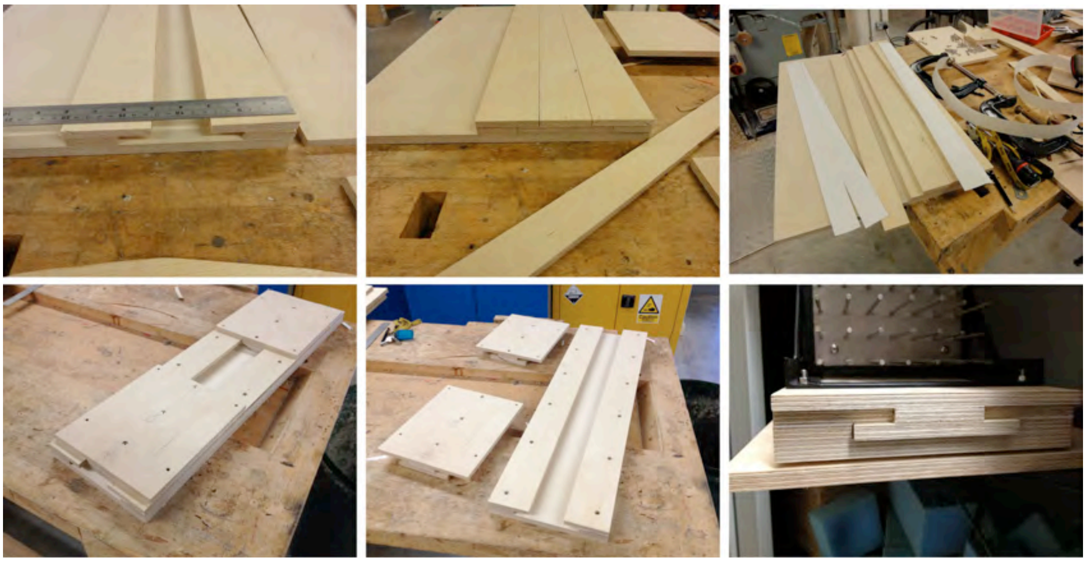


Fig. 71 The rail and sledge system being developed, photos: T. Jørgensen, 2012.

Another issue which had to be resolved in terms of the function of the rail and sledge system was the facility to lock the sledges firmly in position on the rails. This issue, while critical to the overall operation of the system, had not been addressed in any of the early concept prototyping cycles. The criterion for this aspect was the facility to lock the sledges securely and quickly after the foam had been compressed between the pin units to facilitate the cutting of the foam. This solution (just like most other features of the system) was developed through practical prototyping rather than pre-planning and preparatory designing, with the locking mechanism developed while experimenting with the plywood rail and sledges. The mechanism was implemented as a modification to the sledges rather than creation of an entirely new sledge system. This modification consisted of a small section of the lower profile being cut off with a metal nut embedded into the ply. A corresponding bolt inserted from the top part of the sledge enabled the separated section to be drawn up and thereby acted as a secure clamp around the rail. This locking mechanism could be considered a very primitive approach, but through the testing of the system it proved to be a highly effective and reliable solution.

The development of the locking mechanism perhaps highlights the notion that innovators when operating in a field outside their specialist knowledge (Smith, 2005) have the potential to be able to contribute solutions that are more simple than a specialist in a particular field would otherwise implement. It could be argued the construction of this kind of RPT system would normally reside in the field of mechanical engineering, and as the researcher has no background in this field the implementation of this simple yet effective solution may illustrate this notion pertinently. The development of the sledge locking method was recorded in the research journal, illustrated in Fig. 72.

Fig. 72 The development of the sledge locking mechanism logged in the research journal.

The last remaining aspect of the core mechanical foam RPT system was the brackets for holding the pin units on the sledges. A version of this aspect was initially constructed by welding sections of mild steel. However, at an early stage in the testing phase the welded brackets were discovered to suffer from high levels of inaccuracy. This inaccuracy was deemed to have been the result of distortions caused by the welding process. It was not possible to remedy this inaccuracy without constructing an entirely new set of brackets. Rather than trying to recreate another set using the same approach, alternative ones were constructed in sections of extruded aluminium that were bolted together. The brackets made via this approach were also initially found to suffer from a degree of inaccuracy, but these issues could easily be remedied by repositioning the various aluminium sections and overall this approach enabled several other on-going adjustments and alterations.

This example highlights the impact a prototyping approach can have, in particular, to the notion of adopting approaches with a high degree of flexibility, as Schrage (1999) repeatedly highlights. Clearly the first approach of constructing the frames by welding sections of steel together did not correspond well to this statement. In contrast, the researcher’s second attempt with the aluminium profiles, which was based on its flexibility, is entirely aligned with this position, and resulted in a much more successful outcome.

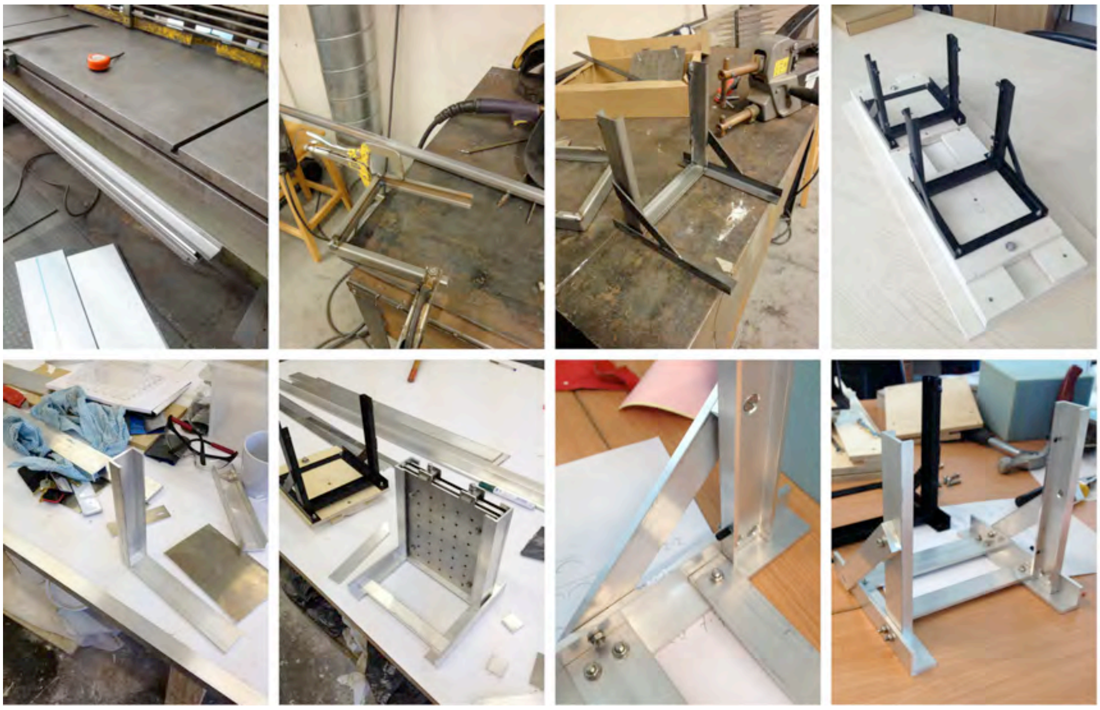


Fig. 73 The importance of using flexible prototyping approaches. The top row of images illustrates the welded pin unit brackets (non-flexible), while the bottom row is showing the bolted aluminium profile brackets, a far more flexible prototyping approach, photos: T. Jørgensen, 2012.

7.2.5 Developing the Pin Tip Designs

Alongside the development of the pin units and the rest of the system's mechanical operating concept, an exploration of the pin tips was also undertaken. As a result of the contextual review the researcher was aware of the work of other researchers exploring this aspect of the RPT concept. Some of the various pin types established by these researchers were recreated as CAD drawings and realised in physical form via 3D printing. For this fabrication process the researcher had access to Falmouth University's Stratasys FDM 3D printer.

As highlighted in the contextual review, Stratasys has long been producing commercial 3D printers based on this ALM principle. The researcher used the Stratasys system as it was readily to hand as a university resource, but the pin tips could have been realised equally well on one of the many inexpensive RepStrap machines that also employs the FDM principle. Therefore, the production of these pin tips could have very easily have been carried out in a scenario where the innovator did not have access to university resources.

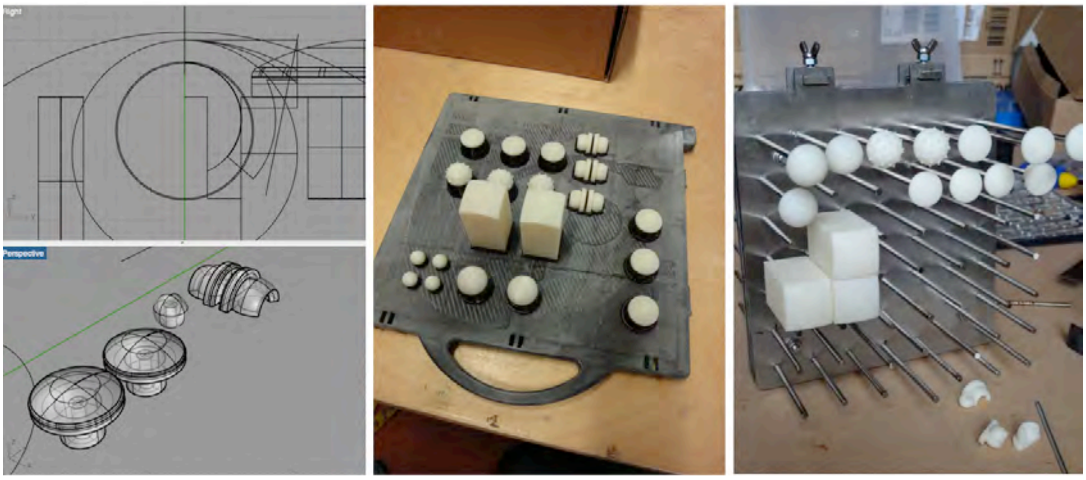


Fig. 74 Explorations of various pin tips facilitated by CAD and FDM 3D printing, photos: T. Jørgensen, 2011.

After the production of the various pin tips, several cycles of practical experimentation with this designs were then carried out. These explorations were again structured along Schrage's notion of 'serious play' (1999), where the researcher would, through practical experiments, seek to gain tacit knowledge of which type of pin tip design was going to be the most likely to deliver good performance in the foam RTP system.

These experiments also included a design for a new type of pin tip developed by the researcher that was specifically intended for the foam moulding application. This tip was designed as a hemispherical dome (20mm in diameter) with a number of small spikes positioned around the dome to enable the tip to *grip* the foam (see Fig. 75). This gripping facility was aimed at preventing the foam from slipping off the pin units during the compression stage, which was identified as an issue in early prototyping explorations.

Following these explorations, the spiked tip design was assessed to be the most suitable option, and a full contingency of these tips were produced via FDM to enable the testing of the complete foam RPT system.

Fig. 75 Spiked pin tips designed by the researcher. The image on the left shows the pin tips still on the printer platform, photos: T. Jørgensen, 2011.

The development of the pin tips marked the completion of the core foam RPT system. With the system now developed, the process of testing and exploring the capabilities of the system could now be undertaken. While the overall mechanical concept was established at this point, alterations to improve the performance of system was continuously implemented throughout the initial testing process (Key Stage 1) through iterative cycles of analysis and adaptations based on action research methodology (subsection 6.1).

The complete foam RPT system is illustrated in Fig. 76 with explanatory descriptions of various elements.

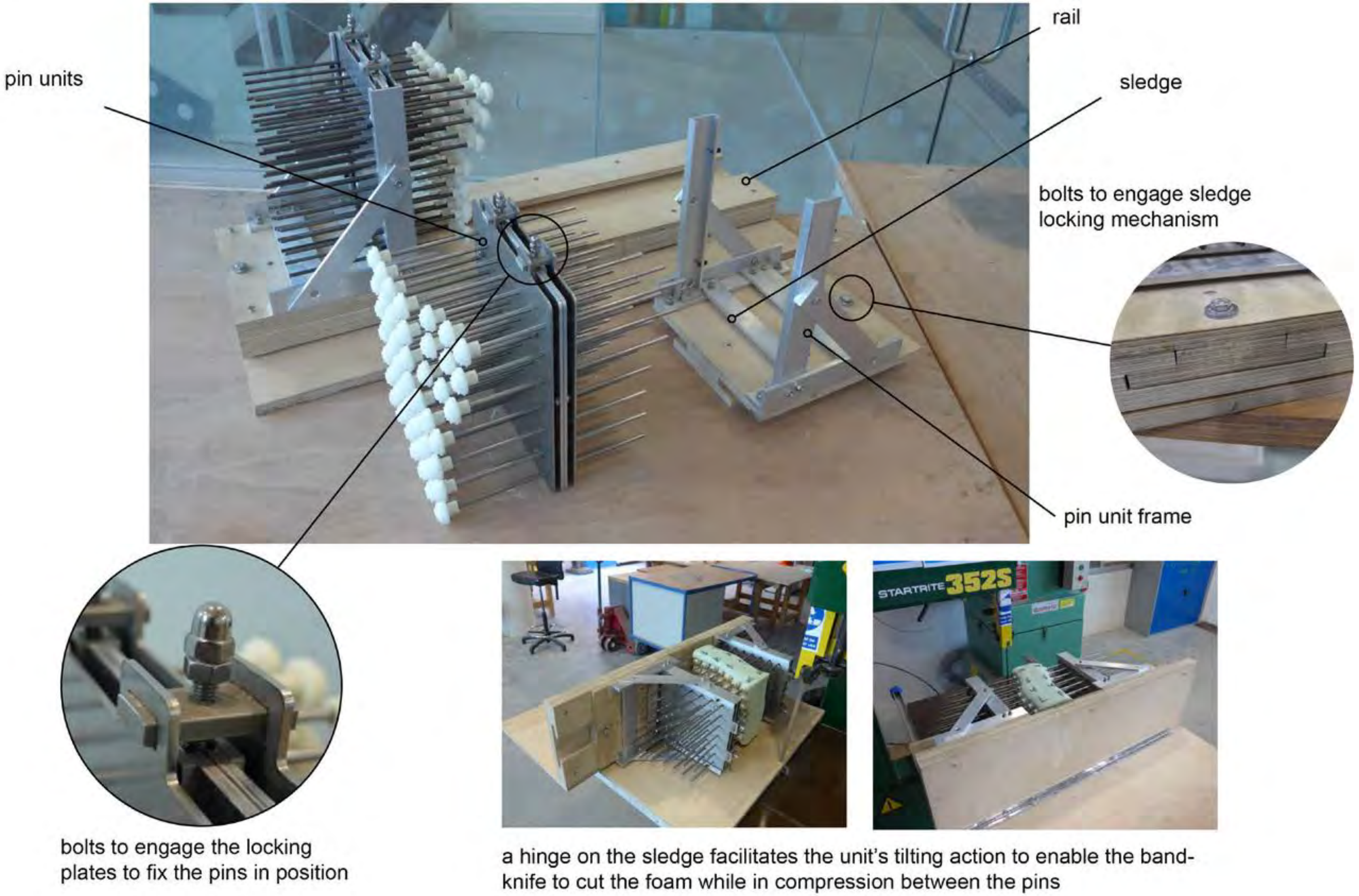


Fig. 76 An illustration of the core mechanical unit of the foam RPT system and the main functional details, photos: T. Jørgensen, 2014-15

7.2.6 The CNC Homebrew Workshop

A central element needed for creating the foam RPT system was the computational, electrical and mechanical aspects — these are elements, which together, could be described as the 'CNC unit'. Generic CNC operation is still the foundation of almost all digital fabrication devices, and as the contextual review also highlights, the proliferation of knowledge, tools and equipment to build CNC machines has grown significantly over the last decade. This part of the practice enquiry was intended to investigate the process of building a CNC from an independent innovator's perspective.

There are many Internet sites and online forums that provide information to facilitate self-builders with the know-how to construct CNC machines independently. However, the value of undertaking such developments with face-to-face peer group support in a physical environment is also strongly evidenced from initiatives such as Hacker spaces and FabLabs (as highlighted in the contextual review).

The researcher sought to explore such a physical, peer group, learning environment by taking the initiative to organise a three day CNC Homebrew machine building workshop at Falmouth University in July 2011. The workshop aimed to bring together a multidisciplinary group of practitioners to build CNC machines. The group gathered included members of the Autonomatic Research Group, along with staff from the Contemporary Crafts and Digital Media Courses. The aim of this workshop was to investigate all the practical challenges involved with the self-building process of CNC systems. This investigation was done through the construction of two CNC machines, with one of the machines based on a standard three axis Cartesian CNC construction and intended for experimental CNC drawing applications. Another machine was developed as a digitising device with a rotating platform. An experienced CNC self-builder, David Turtle from the Royal College of Art, was employed as the instructor for this workshop.

Fig. 77 The CNC Homebrew building workshop at Falmouth University, photo: T. Jørgensen, 2011.

The majority of the elements used for the construction of these machines were standard off-the-shelf parts such as, bearings, belts, electronics and stepper motors. The aluminium profiles used for the main frames of the two machines were supplied already cut to specified sizes, which is a standard service that is offered as part of the supplier's online ordering system.

In order to complete the machines within the three-day duration of the workshop, David Turtle had done a considerable amount of preparation work by pre-fabricating some of the non-standard parts that were needed. These elements included pulley housings and various fixing plates. However, the more experimental aspect of the constructions, such as a mechanism for actuating the drawing tools and the digitising probe, was left for the group to resolve through experimentation. The workshop resulted in the successful development of both machines.

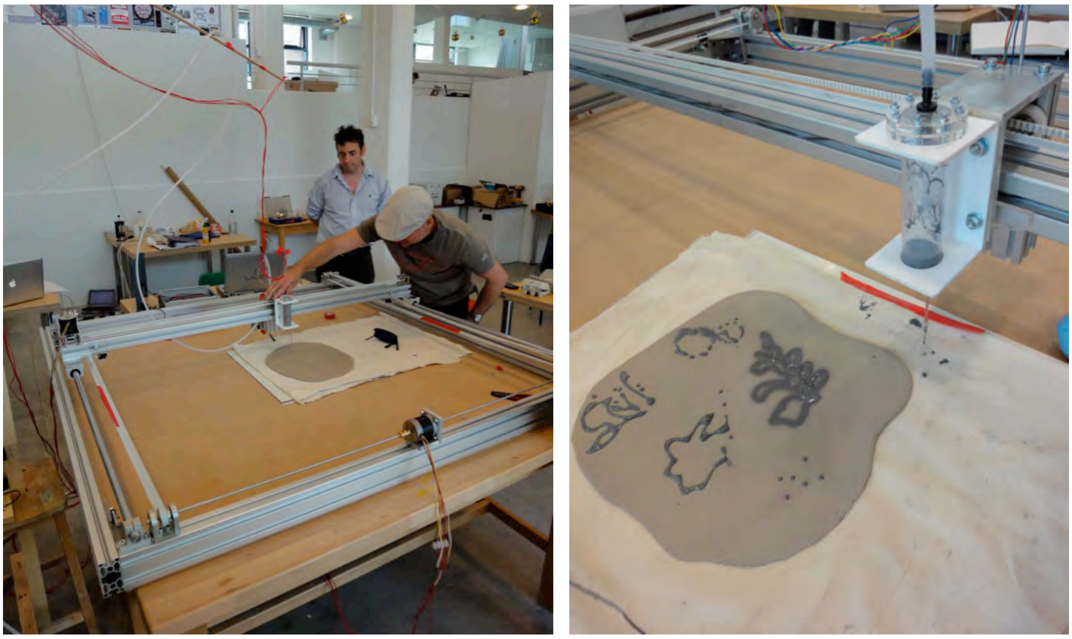


Fig. 78 The three axis Cartesian CNC machine created during workshop, illustration of the clay slip drawing experiments of the left, photos: T. Jørgensen, 2011.

In addition to a pen and brush drawing facility, a clay ‘slip’ drawing system was also developed in this workshop.The researcher was particularly involved with the creation of a digitising probe for the CNC machine with the rotating platform. This element of the device was created using found materials, such as a drawing pin, elastic band and brass tubing. The probe was constructed through extensive use of a hot glue-gun, see Fig. 79.

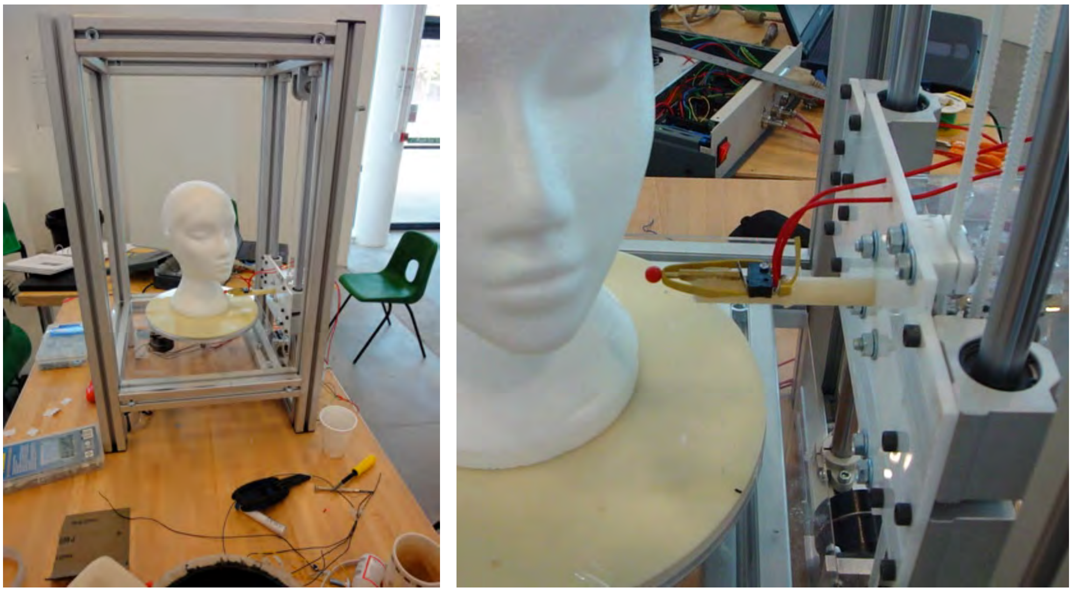


Fig. 79 The digitising machine, with the digitising probe developed by the researcher, photos: T. Jørgensen, 2011.

It is important to highlight that no blueprint or drawings was done to guide construction of these CNC devices, with the development of both machines done through direct making and experimentation. This approach of direct construction though physical experimentation has previously been highlighted as a characteristic methodology for activities associated with the Hacker and Maker Movement sub-cultures. This was an approach that was adopted consciously in this workshop and also evident throughout the development cycles of both practice enquiry strands.

7.2.7 The Development of the CNC aspects of the Foam RPT System

The hands-on knowledge gained from the CNC Homebrew workshop were a very significant factor in enabling the researcher to undertake the construction of his own CNC system. This workshop provided evidence of the value that a physical peer group learning environment can present (such as the FabLab and Hacker Space concepts).

The following section will describe the development of the various aspects of the CNC system developed independently by the researcher for the foam RPT system. With the CNC development phase of the project the same developmental approach was used that was employed in the CNC Homebrew workshop, with no design blueprints carried out prior to the construction, and the form and operational aspects of the machine emerging through physical prototyping.

7.2.7.1 The Mechanical Parts of the CNC System

While no diagrams or design drawings were created prior to the construction of the CNC machine, the development was still guided by the researcher's vision for the machine. The CNC machine was proposed with a classical Cartesian set-up, but envisioned to operate on its side, with the X axis moving in a vertical direction, the Y axis in the horizontal direction and the Z axis in a 90º opposing angle to X and Y, (see Fig. 80). The reason for positioning the CNC operation in this way was to enable the pin units to be set with the pins placed in a horizontal position, which meant that they could be completely *unlocked* and free to move without this risk of them sliding out of position due to the force of gravity.

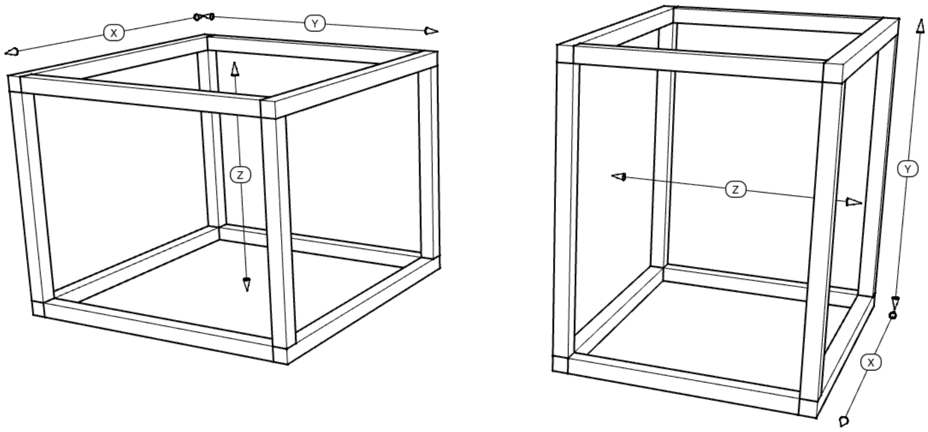


Fig. 80 Two of the CNC set-ups employed by the researcher. A classical Cartesian construction is illustrated on the left, while a rotated version, which was used by the researcher for the foam RPT system is shown on the right. This orientation of the axes prevents the pins from sliding out of position during the setting stage.

The concept for the basic mechanical construction of the system was based on the experiences gained during the CNC Homebrew workshop. The X and Y axes were both constructed to operate with stepper motors directly driving (without gearing) a carriage via toothed belts and pulleys. The operation of pushing the pins into position (via the Z axis) was envisioned to be done as a rod operated via a rack and pinion principle.

Just like the CNC homebrew machines, the basic frame of this machine was constructed by standard aluminium profiles, and the researcher also used the same online supplier, KJN (KJN Aluminium Profiles, 2013) for these profiles. The facility of using the supplier's cut-to-order service was again a significant aid in the construction of the CNC machine as all the frame elements could be supplied cut accurately to the specified sizes at relatively low cost. These sections could then be assembled with standard fasteners making the construction of the basic CNC frame a very easy task.

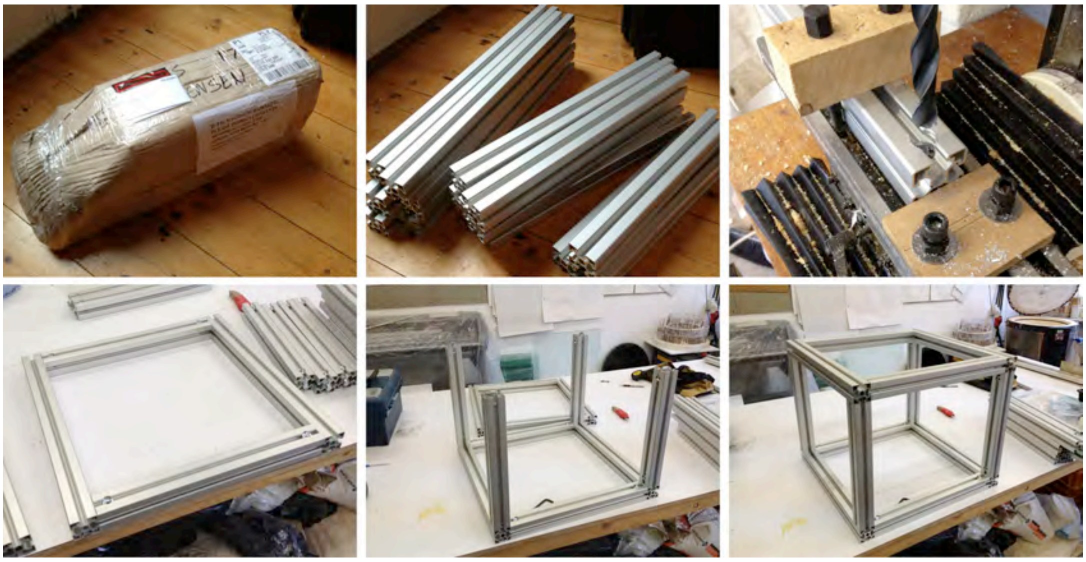


Fig. 81 The construction of the basic CNC machine frame from cut-to-order aluminium profiles, photos: T. Jørgensen, 2012.

Other construction elements, such as linear rails, bearings and stepper motors were also sourced as off-the-shelf parts supplied by Zapp Automation (Zapp Automation Ltd, 2015) — a UK based parts supplier used by many CNC self-builders. Other specialist elements, such as pulleys and toothed belts, were sourced via other online retailers.

While the system was mostly constructed by using ready-made parts, the researcher did find it necessary to custom make certain parts of the machine — just like the CNC homebrew machines. Again, these parts included the pulley housing, stepper motor mounts and a variety of other brackets. To make these elements the researcher developed an approach where such parts could be made from cut sections of standard aluminium profiles. The main tools needed for fabricating such parts via this approach, were simple and affordable power tools, in particular a compound mitre saw and a small manual milling machine. Paper templates designed using CAD were used to help to accurately position various holes and slots as illustrated in Fig. 82.

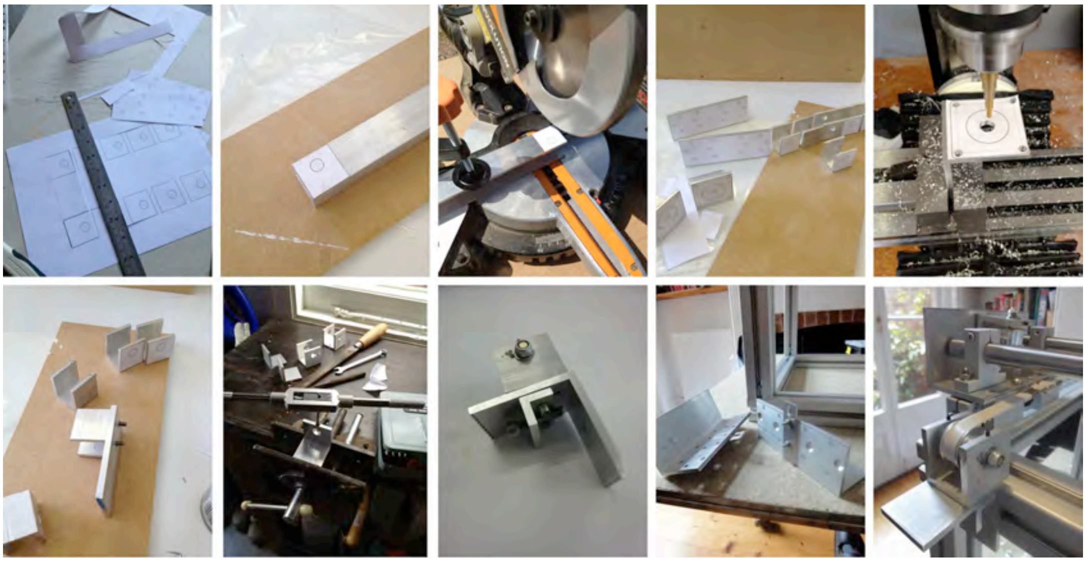


Fig. 82 The production of custom brackets for the CNC system, photos: T. Jørgensen, 2012.

This approach of using standard and inexpensive machinery with readily available off-the-shelf parts corresponds to the situation faced by many independent innovators with limited resources. As a further illustration of this point, the construction of the CNC machine was carried out predominantly in the researcher's own garage and dining room. These situations can be seen as a very typical environment for the independent innovator and as this study was aimed to be carried out as a naturalistic research enquiry (Gray and Malins, 2004, pp.72–73) these situations provided a highly relevant context both practically and conceptually.

Fig. 83 The researcher's main construction areas (dining room and garage), photos: T. Jørgensen, 2012.

It is also very relevant to highlight that access to a wide variety of aluminium profiles through a local metal stockholder, ABS Metals (Abs Metals, n.d.), was noted by the researcher as a significant aid in the development process of the CNC machine. While aluminium profiles are widely available through many online suppliers, the facility to acquire small sections of profile at very short notice was extremely useful. Equally, the facility to physically inspect the suitability of a particular profile section at first-hand was also considered to have been important in facilitating a good rate of progress in the development of the CNC machine.

These aspects highlight the value of a local supply network and could be argued to constitute a notion of Flexible Specialisation (Kumar, 1995) as discussed in the contextual review.

The complete CNC machine created by the researcher is illustrated in Fig. 84.

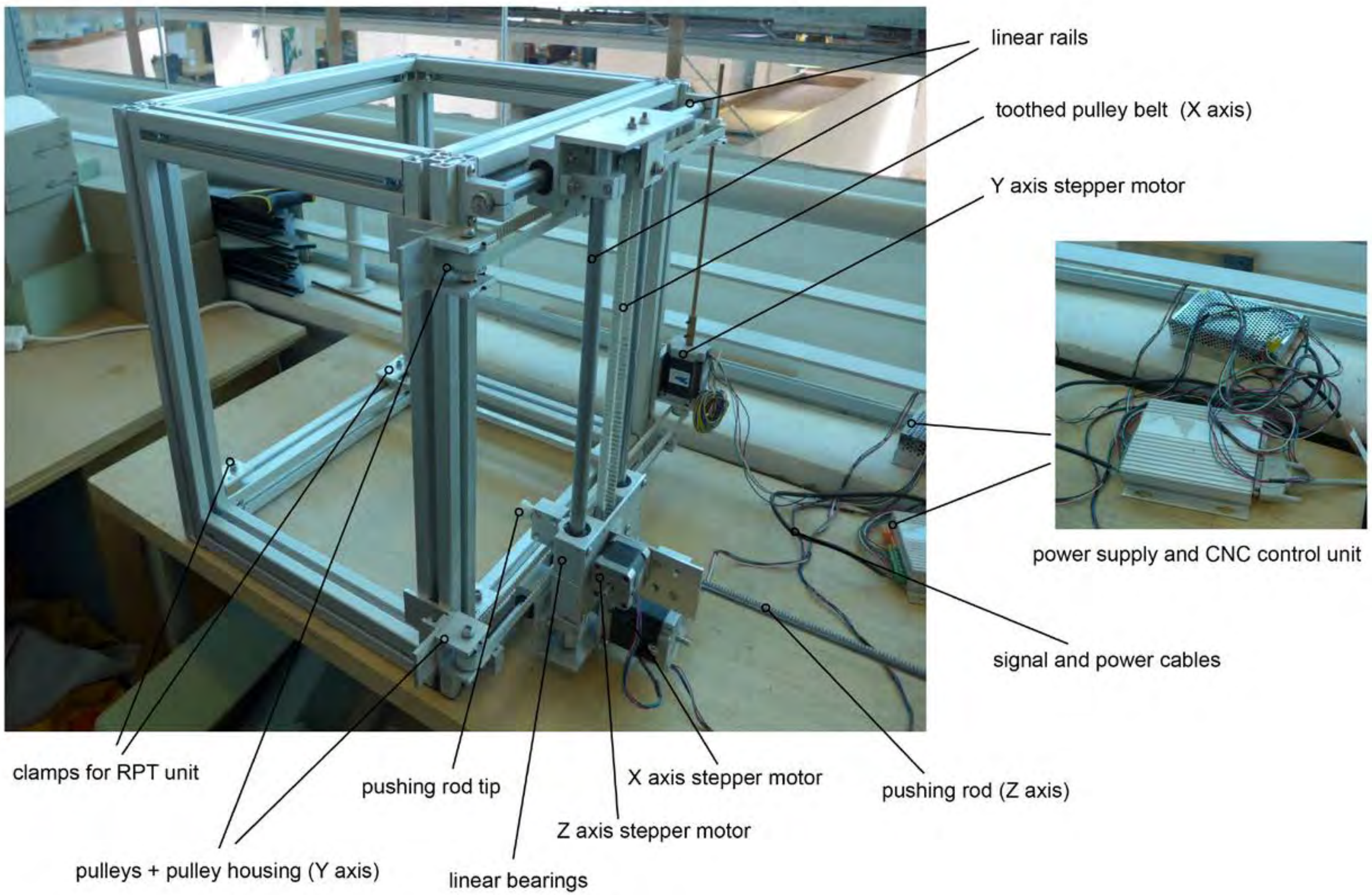


Fig. 84 The completed CNC unit created by the researcher to enable digitally driven setting of the pins in the foam RPT system, photos: T. Jørgensen, 2014.

7.2.7.2 Establishing the Electronic and Computational Elements

As mentioned in the previous text, many of the mechanical parts for the CNC machines were sourced as of-the-shelf parts and assembled into a complete system. When it comes to establishing the electronic aspect of a self-built CNC system, the current environment seems to support a similar approach. The contextual review also underlines this situation by identifying how a significant number of suppliers are now established to supply the self-build CNC sector. These suppliers cater for a wide range of levels of self-build engagement, ranging from complete ground-up constructions to easy assemble kits. The widespread availability of ready-made electronic parts with embedded micro controllers has a very significant role in facilitating innovation in digital fabrication. This situation enables individual innovators, without advanced skills and knowledge of these particular elements, to focus on the actual applications for bespoke CNC systems rather than on the minutiae of getting a basic CNC system up and running.

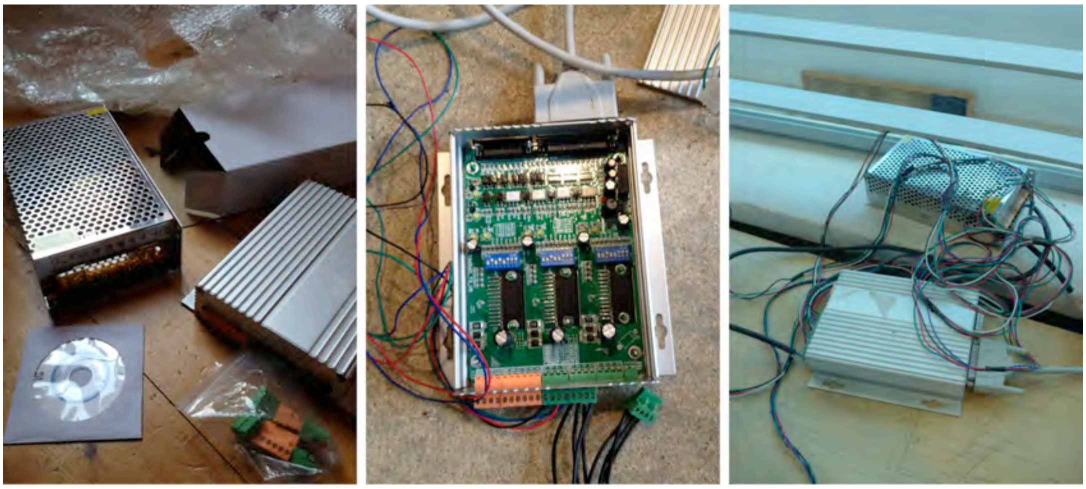


Fig. 85 The CNC controller unit and power supply, both brought online ready-made. Some custom settings had to be applied (central image), but otherwise the units just needed to be wired to the stepper motors, photos: T. Jørgensen, 2012-14.

In the case of the CNC Homebrew workshop the microcontrollers and other electronic parts were supplied by Routout CNC (Routout CNC Ltd, 2011). The stepper motor controllers, CNC motherboard and power supply were all bought via this suppliers as separate parts and wired together with stepper motors sourced from a different company. Some knowledge of electronic wiring was necessary to carry out this task, but it is worth highlighting that many of the CNC part suppliers, including Routout CNC, offer good online manuals/documentation and usually also email and phone support.

Unlike the machines built during the CNC Homebrew workshop, the researcher constructed his own CNC system with a much more complete CNC controller unit, which already had an integrated stepper motor microcontroller. An external power supply was the only other element needed to create a complete electronic CNC control unit. Both the CNC controller unit and the power supply were sourced as new parts from an *eBay* listed supplier. Such parts are readily available through many suppliers at low cost with a wide range of capacities and features.

Fig. 86 Screen grab (2011) of some of the CNC parts offered by a typical *eBay* listed supplier.

Another key element for establishing the CNC system was the software to enable transmission of the data instruction for the movements to the CNC controlling unit, which then in turn, transmits the signals to the stepper motors for these to implement the actual movements of the machine.

The CNC software used for the machines built in both the CNC Homebrew workshop and the glass RPT system was the low cost MACH 3 software. As has been outlined in the contextual review this software is widely employed throughout the CNC self build community.

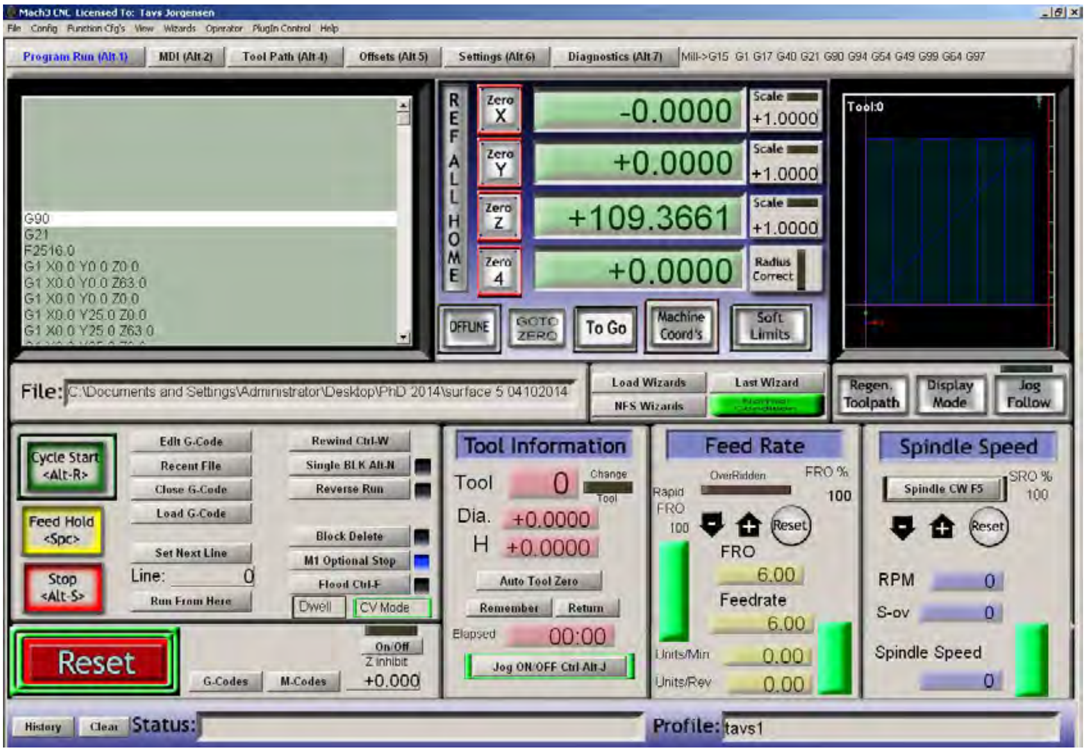


Fig. 87 The interface of MACH 3. G-Code data is loaded on the left and visualisation of tool path (in this case the setting test shape 5) is shown in the top right corner.

Another required element to make the CNC system operational is a way of formatting the instructions that tells the CNC system what to do. These instructions are usually in the shape of G-Code commands. G-Code is essentially a set of coordinates compiled into a simple list that directs the CNC devices to carry out the machine tool movement. The G-Code commands are also known as 'tool-paths' and these paths are usually created by using CAM Software. While a number of low cost (or free) CAM software packages already exist, these tend to be somewhat limited in capabilities and might not fit more non-standard CNC applications, such as the setting of pins in an RPT device. Therefore the potential to make bespoke CAM software significantly extends the possibilities for creating novel and innovative CNC based fabrication systems.

Until very recently the creation of such software required high-level programming skills. However, visual scripting tools such as Grasshopper, as well as other more accessible programming environments, are becoming increasingly common. These enable individual practitioners, without advanced coding skills, to construct bespoke software programs or scripts to suit their particular needs. The CNC Homebrew workshop offered the opportunity to test the potential for creating and using such scripts. Prior to this workshop, David Turtle had created a bespoke

CAM script in the Grasshopper environment, specifically for the use in the workshop. The initial aim for the machines build during this workshop was to explore various CNC enabled two-dimensional drawing applications. Therefore, the particular Grasshopper CAM script was developed to translate vector drawings in the Adobe Illustrator format into G-Code commands. Although somewhat crude, this definition was found to work reasonably well for this purpose.

The researcher used the experience gained from the CNC Homebrew workshop to initiate the development of another Grasshopper CAM script (also known as a definition) specifically for the use with the foam RPT concept. The requirements for this definition were somewhat different from the definition developed for the CNC Homebrew workshop, with the RPT application the process of setting of the pins pre-dominantly requiring a plunging action rather than the interpretation of two-dimensional linear moves. Consequently, the Grasshopper definition for this purpose had to be scripted almost entirely from scratch.

Another aspect that the researcher sought to utilise further was Grasshoppers' integration with the main Rhino 3D modelling environment in order to develop an integrated design and CAM module (CAD-CAM). Rhino 3D has extensive capabilities for creating and editing Non Uniform Rational B Spline (NURBS) surfaces in a free form manner. In the Grasshopper definition that was developed by the researcher, a link with Rhino was created to utilise the software's powerful surface manipulation tools. With this link any given surface that is designed and manipulated in Rhino could be directly feed into the Grasshopper definition, resulting in a G-Code ready to implement via the RPT CNC machine.

Like any other Grasshopper definition, the data in the script, created by the researcher, flows from left to right (see Fig. 89 and Fig. 90). The surface design data that is used to set the RPT system is loaded via a surface module at the far left side, which represents the start of the script. Through a number of other Grasshopper modules, which have been linked by data flow lines, the setting data is sampled from a matrix of points on the surface of the shape design. These points correspond to the spacing of the matrix of pins in the physical RPT device, which in this case was 25mm. The sampled points in the Grasshopper definition were translated into CNC moves in G-Code format. This G-code date was designed to continuously update to reflect any changes in the 3D Rhino surface design and this data could then be exported out of the definition as a plain text file.

The file was then loaded into the MACH3 CNC software to initiate the CNC movements to set the pins in the RPT device.

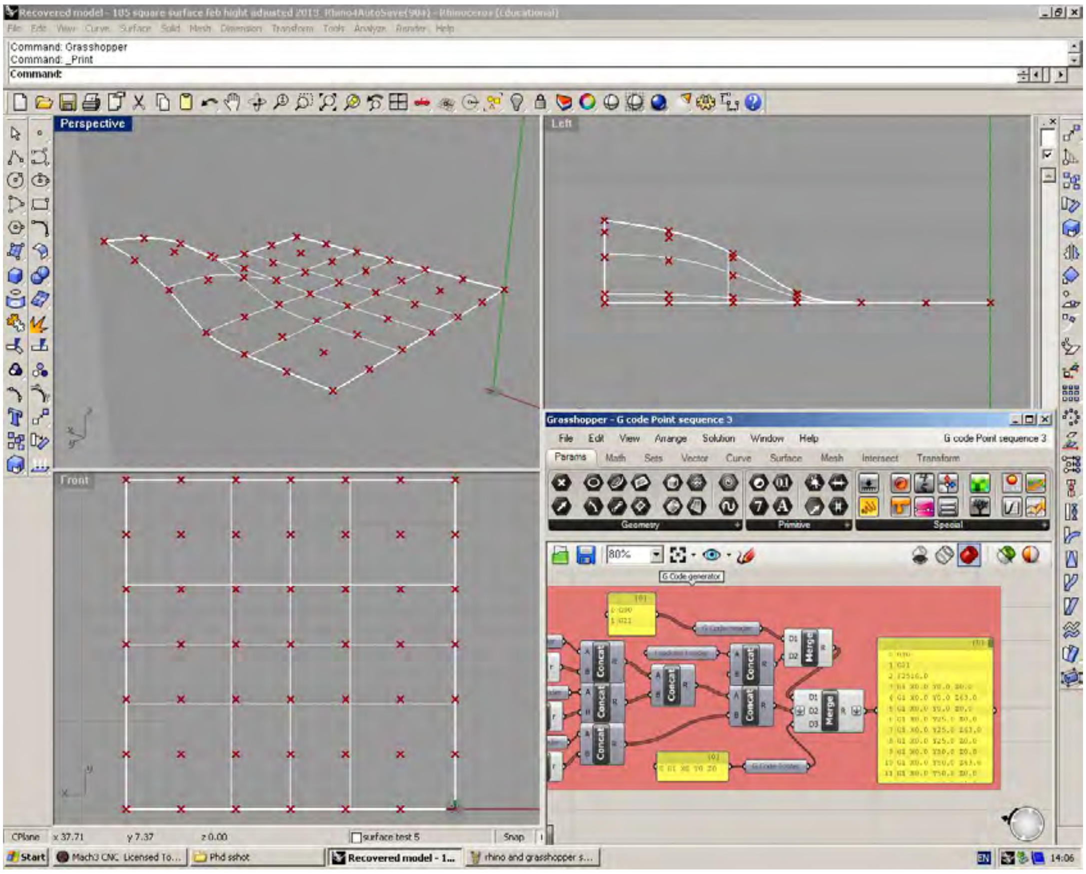


Fig. 88 Screen shot of a test shape design within Rhino. The red crosses are pin location points calculated by the Grasshopper definition. The resulting G-Code is shown in the bottom right corner in the floating Grasshopper window.

Initially, this script was created for dealing with a surface area that related directly to the size of foam RPT system. However, an extended Grasshopper definition was later developed (Fig. 90) which could deal with surfaces larger than the size of the RPT device. In this definition the surface was split into four equally tiled elements with the corresponding G-Code outputs also split into four streams (A, B, C and D). This extended script meant that surfaces four times the size of the RPT device could be moulded and, in principle, this capacity could be extended to deal with even larger surfaces.

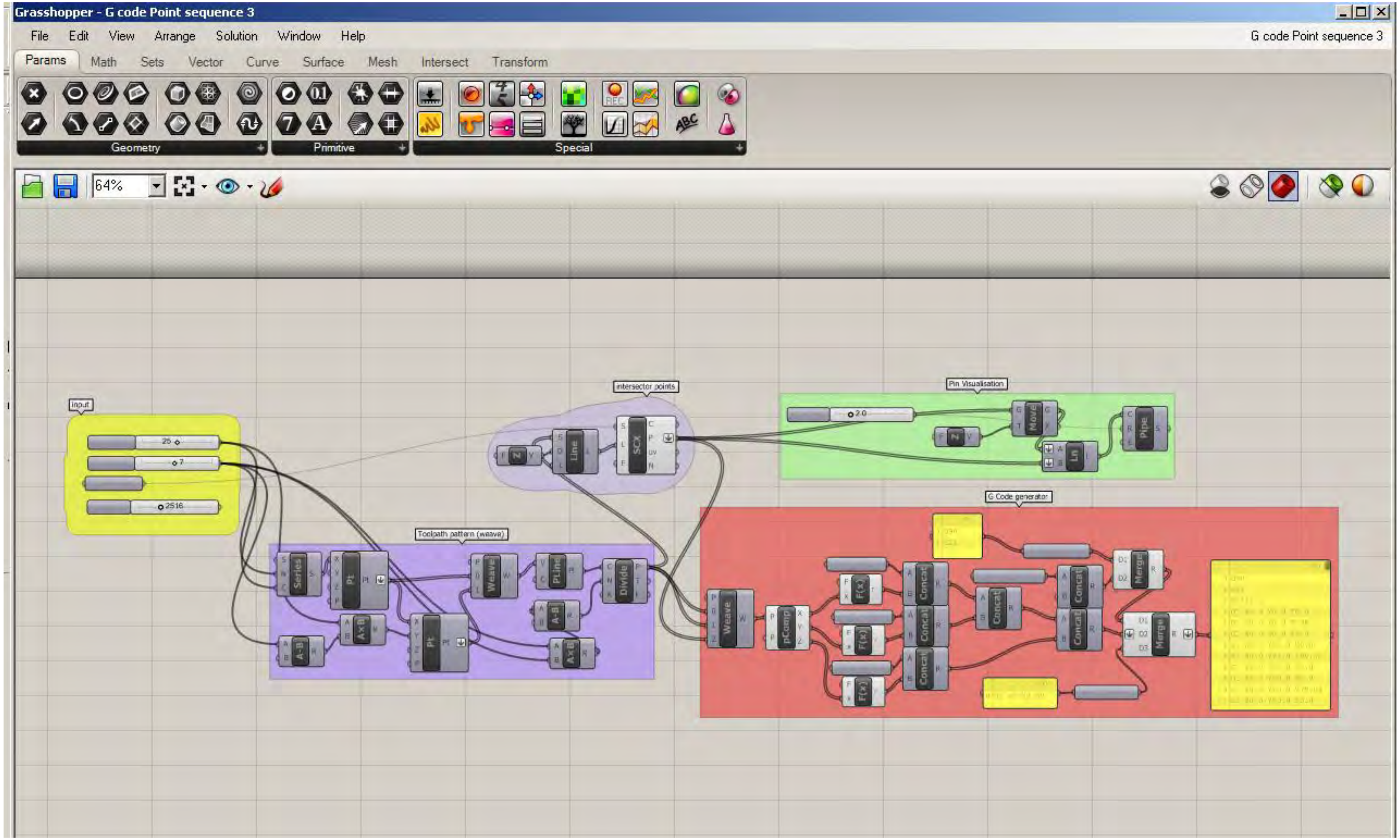


Fig. 89 Grasshopper definition for processing a single shape design into G-Code commands for the foam RPT system.

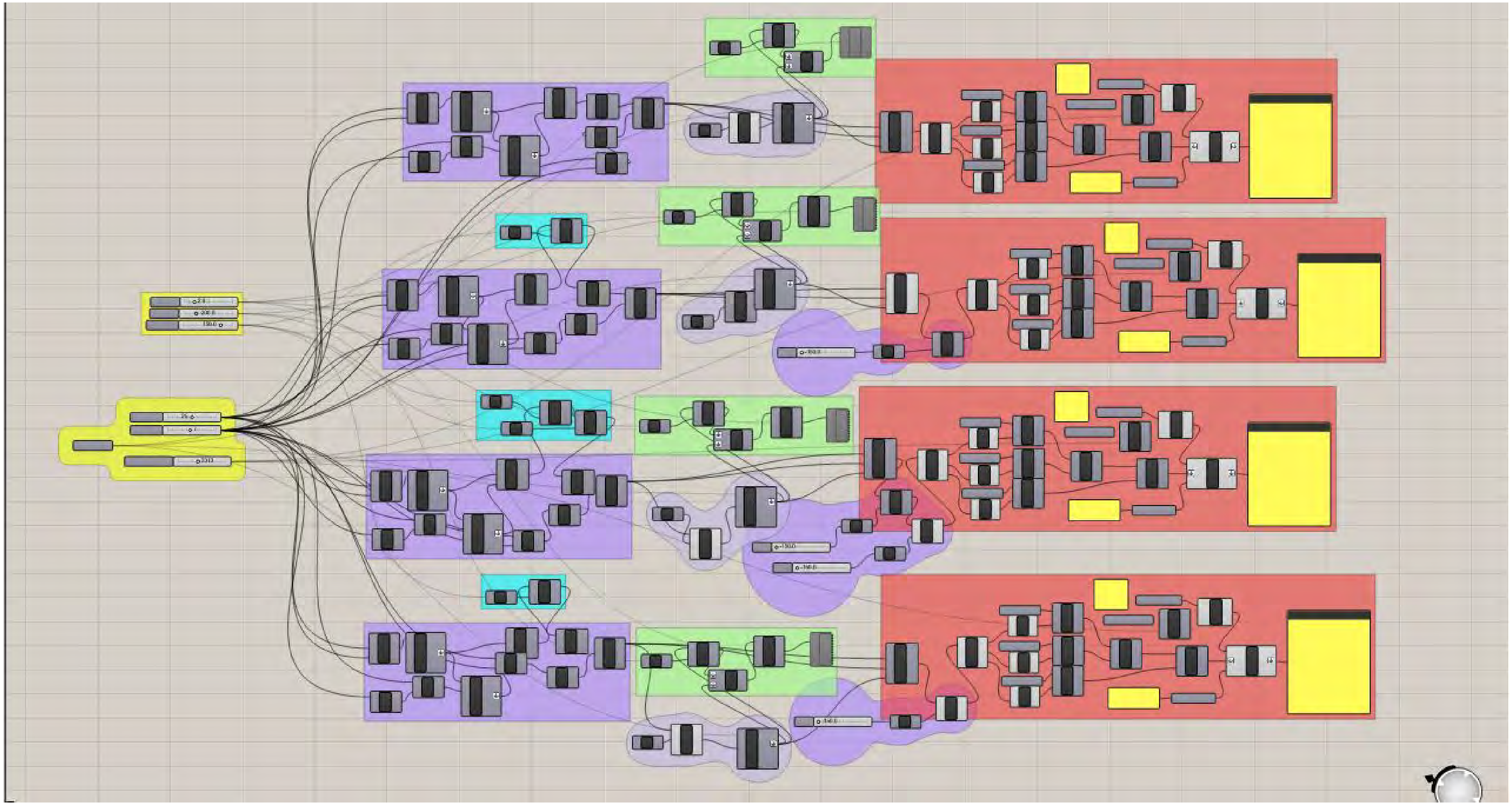


Fig. 90 The four way G-Code generating Grasshopper script which enables the design and fabrication of tiled foam shapes with the foam RPT system.

The process of combining all the various elements (mechanical, electrical and computational) to establish a complete CNC system was done over several months. This process was fairly straight forward, however, many aspects of the system were further developed and improved throughout the Key Stage 1 phase in response to emerging findings from the tests results.

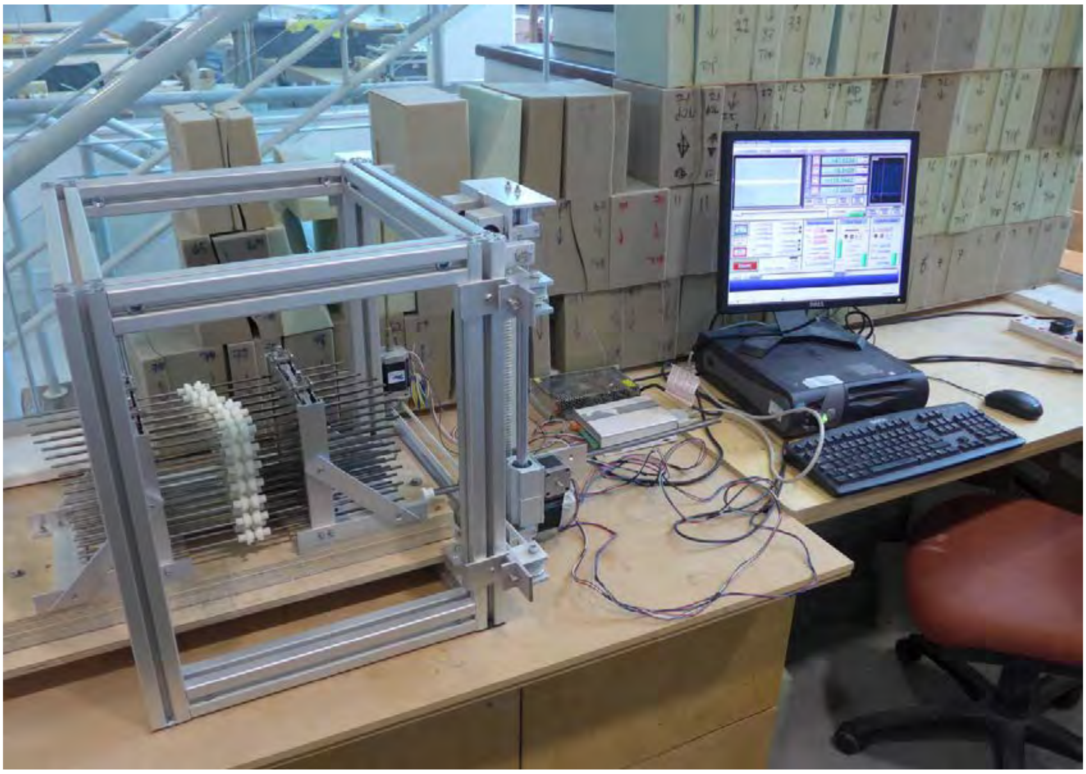


Fig. 91 The complete foam RPT system. The cutting stage was implemented on a bandsaw machine located nearby and therefore not included in this image, photo: T. Jørgensen, 2014.

7.2.8 Developing a Digitising Facility with the System

The process of extending the CNC unit with a digitising capability was undertaken at a much later stage than the initial construction phase of the core CNC system — essentially it was carried out as a retrofit.

The development of this facility was partly driven by an investigation to test the fitting of fabric to the foam shape (which will be described in a later subsection). The facility was also created to enable accurate measurement of the foam shapes produced on the system, thereby facilitating a series of empirical tests which could be carried out on the system to establish its manufacturing accuracy and capacity for replicating forms.

Establishing a digitising capacity with the system was dependent on the creation of a digitising probe to collect the data. In the process of creating the probe, the researcher utilised his experiences from the CNC workshop (see Fig. 79).

The initial design for the probe was developed during this workshop, but was further developed with a 3D printed core body that enabled easy attachment onto the toothed rod, which constituted the Z axis in the CNC set-up.The construction of this probe (just like the initial design created by the researcher during the CNC Homebrew workshop) also utilised found elements, such as a nail, drawing pin and sections of brass pipe.

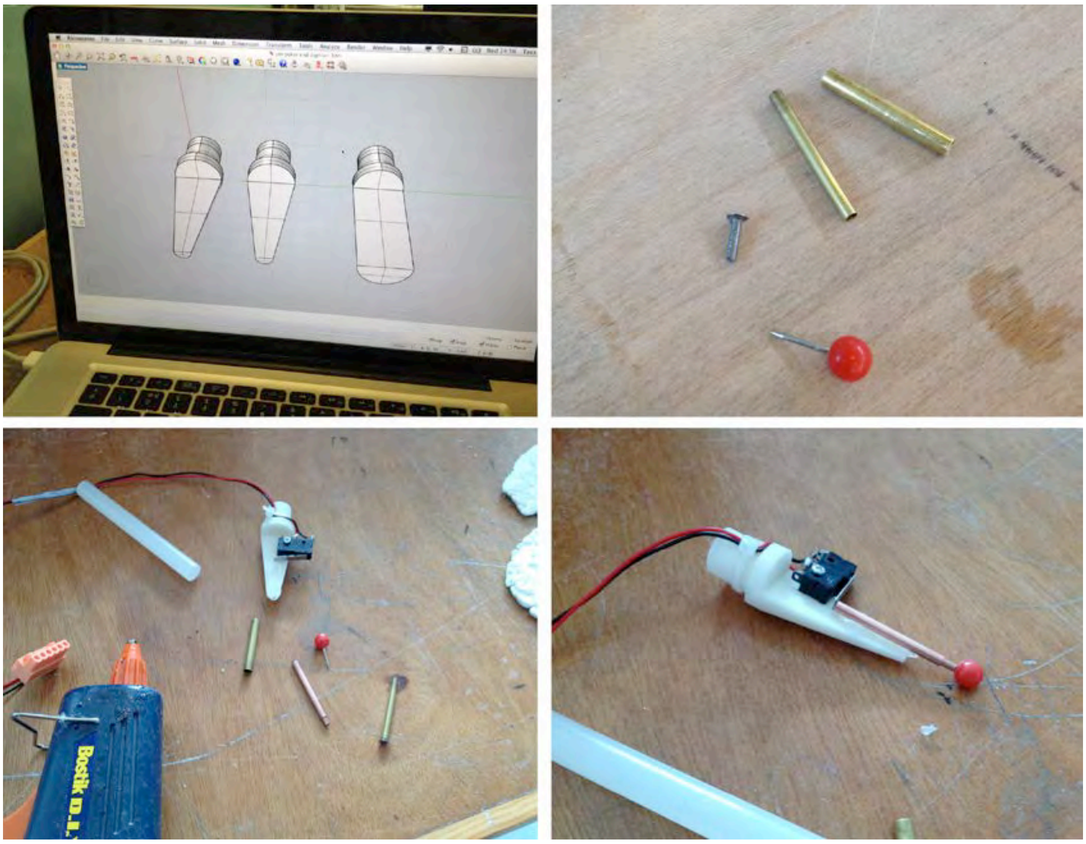


Fig. 92 The creation of the digitising probe to enable the sampling of data points from the foam shapes, photos: T. Jørgensen, 2013.

Initially, the researcher intended to create a special frame to clamp the foam in place during the digitising process, but during this process it was found that the CNC unit could simply be rotated 90º to operate in a classical Cartesian orientation (XYZ). With this approach, a clamping frame was not needed and instead a simple, removable, raised platform (as well as the digitising probe) was all that was used to enable the conversion of the CNC unit into a highly effective and accurate digitising system (see Fig. 93).

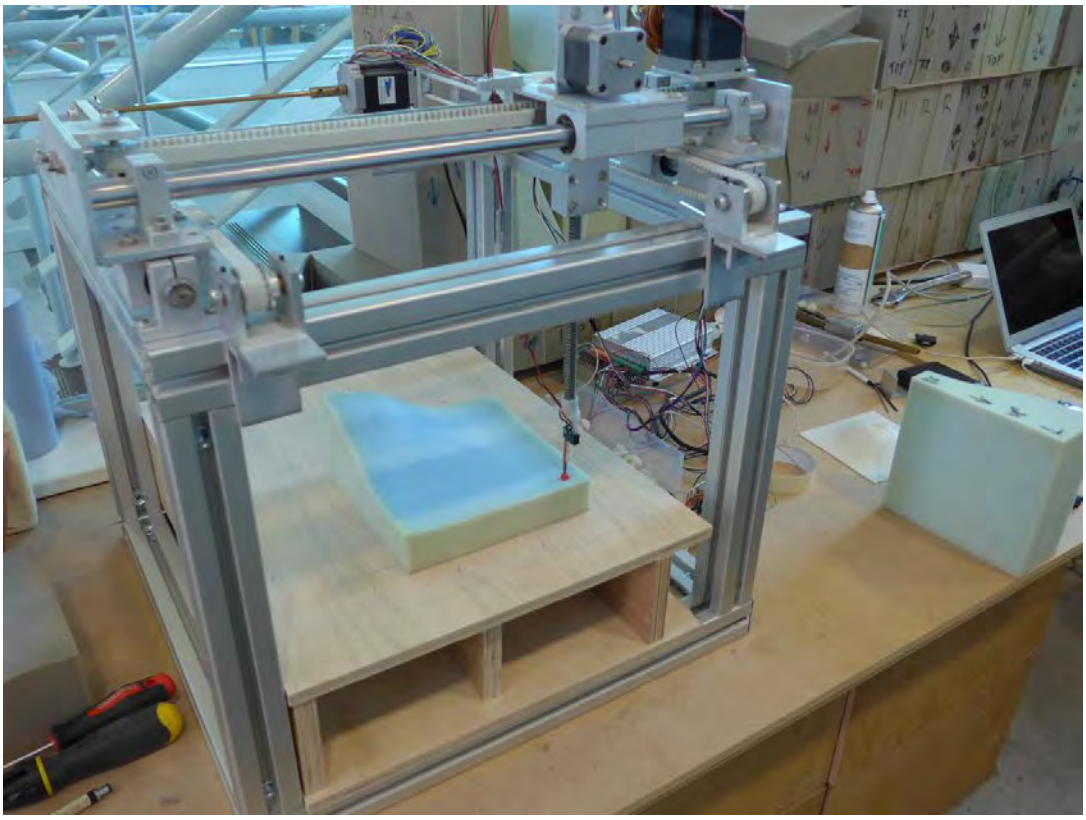


Fig. 93 The CNC unit converted to digitise the foam while operating in a classical Cartesian orientation, photos: T. Jørgensen, 2014.

The software code needed for this digitising facility to operate was found within the MACH3 software. This CAM software includes a number of small extension programs called ‘wizards’ which enable user generated G-Code scripts for certain simple machine tool operation. The list of wizards also includes one for creating G-Code for digitising, which was used to create the code for the digitising operations of the system.

7.2.9 Reflections on the Development of the Foam RPT System

This subsection has covered the entire prototyping process leading to the development of all the core elements for establishing a complete RPT system for an entirely novel application of cutting furniture foam into 3D shapes. Through this detailed description of the development process the researcher seeks to highlight a number of issues which are central for the argument of this thesis.

The study was, from the outset, focused on exploring the current conditions that are presented to the independent innovator to operate in, with a particular focus on the use of digital fabrication tools in the innovation process. At the core of the study is the proposition that it is increased access to design and fabrication tools that, combined with particular developmental approaches, are the primary facilitators for independent innovators to operate in the current environment.

Subsequent subsections will address and analyse the foam RPT system capabilities and the prospects for systems to be used as a viable production concept within a commercial context. With the definition of innovation as a complete process involving an aspect of diffusion (see Fig. 94), usually through commercialisation, the assessment of the foam RPT system's performance in this context clearly has some relevance.

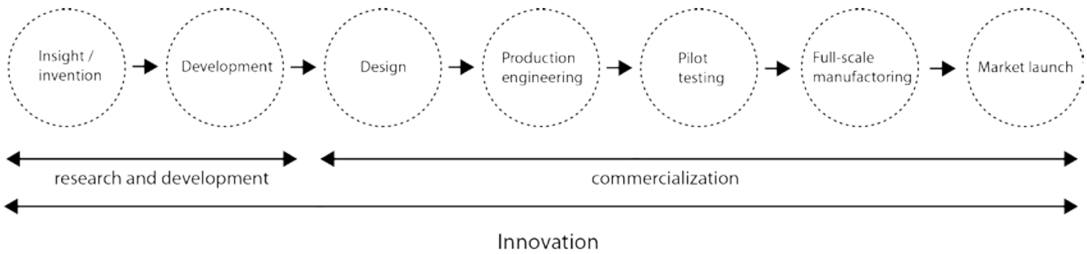


Fig. 94 Generic model of the innovation process, after Smith (2005)

However, the focus of this study is primarily concerned with the earlier phases of the innovation scenario involving the research and development stages. Consequently, the results from the testing stages are considered potentially less important in relation to the core issues of this study, which will be interrogated in the following text.

Firstly, this section has highlighted the notion of developing a concept through practical prototyping and experimentation. Through the contextual review this approach had already been identified as being characteristic for the current innovation methodology in the Hacker and Maker Movement subcultures. It was therefore highly relevant for the researcher to adopt similar development approaches with his work in the practice enquiries. It falls outside the remit of this study to make a full assessment as to what extent this approach is being employed by independent innovators in general, but it is likely that individual practitioners would predominately rely on a practical and experimental approach when innovating, rather than developing ideas and concepts entirely through theory.

Within such an innovation approach there are aspects in relation to particular stages of development that are relevant to identify. In this investigation the researcher identified three aspects of particular importance: speed, *flexibility and accuracy*. These aspects could potentially be seen as conflicting, for example achieving a very high level of accuracy is not unusually compatible with very fast prototyping, and the researcher is not proposing that all three aspects should be attempted in the same cycle of development. Rather, that these particular aspects have been identified in this study as being of particular importance in certain stages of the innovation and prototyping process. In terms of the development stages, the researcher considers the following to characterise this particular practice enquiry: early exploration stage, concept development stage, construction stage, testing stage and finally a refinement stage.

The researcher believes that identifying which of the aspects of development (speed, flexibility and accuracy) should be in focus at any particular prototyping stage to be critical in achieving a successful development process. Examples drawn from various development stages of this practice enquiry, with the associated development aspects, are discussed in the following text.

The researcher is not normally inclined to work *fast and roughly*, but instead much more inclined towards *neatness and perfection*. However, through the experience of adopting a 'quick and dirty' approach (Schrage, 1999) in the early exploration stages, he now fully recognises the value in this approach. An example of the value of this approach can be drawn from the very early stages of exploration of the foam RPT concept. In this stage the primary task was to establish if the core concept would work before significant time was invested. As a consequence, the role of the initial prototyping session was to gain as much information about the concept as possible through rapid prototyping cycles. The use of found objects and *to-hand* materials as part of this crude system was very useful in progressing the core idea of the concept. This approach enabled the researcher to gain tangible knowledge with the material characteristics of the foam medium and the physicality of the moulding concept in general.

After the initial concept exploration stage, work to expand the foam RPT idea was carried out through a concept development stage, which was done through a foamboard prototyping session. This session focused on developing the outline for a functional system. As the earlier ‘quick and dirty’ exploration stage had already provided a significant amount of tacit material knowledge, the foamboard prototyping stage could be carried out with a high level of material abstraction. This abstraction was facilitated through use of foamboard and card to model the shape of a functional system. This way of prototyping insured this stage of development could also be carried out with very quick design iterations.

In relation to the overall notion of speed in the prototyping process this aspect was found to be one of the key potential advantages of the independent innovator. The researcher considers the absence of an institutional structure provides the opportunity for a high degree of *nimbleness* that enables independent innovators not only to prototype ideas quickly, but also to carry out particular stages of the development processes without a restrictive organisational structure. In this regard, it is relevant to clarify that while the researcher did employ some university equipment in this study the vast majority of the development work was carried out using the his own tools and workspaces. The university facilities that were used could also have been accessed in other ways, for example through community facilities such as FabLabs or the use of commercial bureau services. And while the development of the foam RPT system was clearly carried out within an academic framework of a PhD study, the researcher considers the development process that has been described in the preceding subsection would not be significantly different had it been carried out entirely outside this framework.

As the development of the system moved on from the concept development stage to the construction stage, the aspect of flexibility in the prototype approach became a far more important element than that of speed. At the stage where a fully functioning system was beginning to be established some of the elements required more significant investments. The term *investment* in this context relates not only to the actual cost of parts for the development process, such a laser cut stainless steel elements, but also refers to the significant time needed for developing these parts.

Reflecting on the experiences during the stage of the development, it can be concluded that the prototype, at this stage, should be built with the highest degree of flexibility so alterations and improvements can be made in response to emerging test results. The construction of the pin unit brackets, which have been highlighted in the previous subsection, is an obvious example of the impact of *flexibility*, or more accurately, *non-flexibility*, in the prototyping approach.

The choice of prototyping material is also of significant importance in this regard. A relevant example of this is the use of birch plywood to construct both the rail and sledges of the system. In this case, the plywood facilitated numerous alterations and tweaks while still providing a reasonably structural integrity and construction accuracy.

With the gradual refinement of the system accuracy in the various parts of the construction became a much more critical aspect. At the outset of establishing the foam RPT concept, the researcher had expected the level of engineering tolerances needed to construct the system to be fairly low. But as the research progressed it became evident that the system had to be constructed with a very high level of accuracy in order to address issues of variability and accuracy in the output. Probably the single most significant factor to achieve a high level of accuracies was the facility of being able to get bespoke parts fabricated by a local laser cutting bureau. The laser cutting company which was used by the researcher to fabricate the parts for the system, Luffman Engineering, employs a Salvagnini L3 fibre laser, which is listed as being capable of producing parts with accuracies between 0.08 and 0.03mm (Salvagnini, n.d.).

While bespoke metal laser cutting services have been available for more than a decade, based on the researcher's own experiences the diffusion of such services have grown significantly. Equally, the access to other digital manufacturing methods is also undergoing significant development with companies such as Shapeways (Shapeways Inc., 2011) and Kraftwurx (Kraftwurx, Inc., 2014) offering bespoke fabrication in a wide range of materials. Both of these companies use ALM manufacturing methods, which generally does not deliver the same high level of accuracy that is currently achieved with CNC laser cutting, but the quality and cost is likely to improve with the diffusion of ALM technologies that is currently underway. It is therefore reasonable to expect that the opportunity for independent innovators to get very accurate (and bespoke) parts manufactured by companies using digital fabrication equipment is highly likely to increase.

As has been repeatedly highlighted, this study proposes that it is the increased access to tools which is one of the key aspects in facilitating new opportunities for independent innovators. In relation to the growing opportunities of getting very accurate bespoke parts manufactured by digital fabrication companies. This access to *physical* digital fabrication tools is accompanied by increased access to the software tools for developing the design for such parts. This is generally done via CAD programs, and the contextual review describes how a number of free and low cost CAD programs mean that independent innovators can very easily access such design capabilities.

In this investigation access to design and development software was also shown be a critical enabling role in the innovation scenario. Rhino 3D and Grasshopper were the main programs used by the researcher. However, it is also relevant to highlight the MACH3 software as playing a very significant part too. Without this program to enable the communication of the G-code to the CNC controller a functional RPT system would most likely have not been established. Although none of these three programs are open source they are relatively inexpensive (Grasshopper is free but requires a full Rhino licence to operate it). Equally, the Mac version of Rhino, which was also used extensively in this study, was in a beta stage of development and consequently free to use.

Is it relevant to highlight that these digital design and development tools have now been available for some time. The initial version of Rhino being released in 1998 (McNeel, 2014) and the first MACH software, MACH1, was launched around 2001 (Mauch, 2005). Grasshopper is more recent in being released under the title 'explicit history' in 2007. The growing maturity of these tools in combination with an established user group are now providing a good platform for independent practitioners to utilise for new innovations. It may also be relevant to view these tools in relation to S-curve theory, and that, just like physical tools, the growing diffusion of such tools is highly likely to result in rival software tools entering this particular sector at some point, which in turn may provide even better tools for the independent innovator to use.

However, there are some pontential drawbacks in the success of key software tools for CNC selfbuilders, such as Grasshopper. In the five years the researcher has worked with Grasshopper, the program has developed significantly and a multitude of new features and add-on modules have extended the capability of the software. But the process of extending the capabilities of Grasshopper may now also start to impact on the level of complexity of the software, potentially to a degree where this issue is now starting to become a barrier for novice users to engage with this tool.

A perhaps somewhat overlooked aspect in relation to the aspect of software tools is the issue of portability of thedesign data. By this is meant that data developed in the early stages of the innovation sequence to generate initial prototypes and visualizations can be reemployed at later stages, for example files submitted to external companies to fabricate parts. In the case of the foam RPT system much of the design data used for the creation of early concept models in foamboard combined with printouts from the researcher's personal inkjet printer. The same files used in these early stages were later used to laser cut the metal parts for the functional system. The portability of the design data from an early prototyping stage to the final manufacturing stage was a great aid in this innovation scenario. It is a facility that can be utilized particularly well when parametric digital design tools (such as Grasshopper) are used. Such design tools enable alterations and improvements to complex systems without the need to completely redraw the files.

In the development of the foam RPT system the researcher also made use of many analogue tools, both in terms of hand tools as well as simple machine tools, including a compound mitre saw and small milling machine. The availability of affordable hand and machine tools should perhaps also be noted as a contributing a factor in facilitating independent innovation, although this is perhaps of minor significance.

In addition to the access to tools, it was the researcher’s assumption that access to knowledge and peer support would also be a key facilitator in the innovation scenario. In particular, the researcher expected that online knowledge resources, such as user forums, would play a significant role in aiding the development of the foam RPT system, however, this aspect turned out not to be particularly relevant.

Throughout the investigation the researcher did not find a particular need to engage with online peer networks. A number of online tutorials were utilised, through sites such as *The Digital Toolbox* (digitaltoolbox, n.d.), to develop his skills with Grasshopper. Some general information in relation to the settings for the CNC controller were also sourced from various websites (usually the suppliers), but in general online knowledge resources did not play an overly significant part in facilitating the development of the system. But it is also relevant to note that online resources did play a part in a motivational aspect. Countless sites document how individual practitioners have developed their own particular digital fabrication system, thereby potentially providing others (including the researcher) with the confidence of undertaking their own projects and experimentation.

In contrast to online peer support, physical peer interaction was found to play a far more significant role. The CNC Homebrew workshop was particularly important in providing the researcher with the necessary knowledge and confidence to progress with the construction of his own CNC system. Equally, on-going interaction with other practitioners, suppliers and professionals played a very considerable contribution in the development of the system. This interaction was mostly carried out face-to-face but phone calls and email communication were also used to a minor degree.

Based on the knowledge gained from the investigation concerning the development of the foam RPT system it appears evident that new constellation opportunities are expanding for the independent innovator. These opportunities are being presented through an innovation environment, which is created by several elements. These elements include: access to affordable and powerful design tools; portability of data (from prototyping stages to full system fabrication); the ability to source cheap parts for the construction of the CNC machines from online suppliers and also to the ability to source training and knowledge through online resources. All of the above aspects present opportunities for independent innovation regardless of the physical location of the innovator. But equally, this investigation also appears to provide evidence that the physical, local situation has also a very significant contributing role in contributing to the overall environment for independent innovation.

While many parts of the system were sourced online, local suppliers were equally important in the process of developing the system. The researcher's local area has a significant marine sector and the presence of this industry resulted in the occurrence of suppliers where the researcher could access a number of useful parts; a local non-ferrous metal stockholding firm was particularly useful in this regard. And while parts bought from this firm could potentially have been sourced online, it would most likely have been a far more cumbersome process, involving identifying which particular site to source individual metal sections, with issues regarding minimum quantity order and cost of shipping also impacting negatively on the process.

Being able to use local laser cutting firms was also beneficial in terms of getting an intimate understanding of the capability of the process. Local foam suppliers were also critical to the innovation process, not only in terms of supplying the foam to undertake tests with the system, but also as a very important source of information and advice. Finally it is also relevant to reiterate that it was the interaction with the local industry partner, MARK Product, that provided the researcher with the inspiration for developing the foam RPT concept. Overall, this investigation provides evidence that the infrastructure of local suppliers, subcontractors and small-scale industry is an important factor. A good infrastructure in this regard is likely to provide a fertile environment for independent innovation.

7.2.10 The Testing of the Foam RPT System

It should be evident from the previous subsection that the development process of the foam RPT system was, to a large extent, guided by minor explorative tests to ensure that the system could perform its intended task.

At the point where a functional foam RPT system had been established a more formalised phase of testing was undertaken. This phase was separated into two key stages, with an initial stage where a series of tests were undertaken to establish the capabilities of the system while continually implementing improvements and tweaks. These improvements were informed by on-going feedback from the results of the tests. Such cycles of tests were followed by analysis and then potential improvement being implemented — this process was closely aligned with one of the study's core methodologies of action research (see methodology chapter, subsection 6.1).

The series of tests undertaken at this stage was later labelled as: 'Key Stage 1 tests', and nearly 90 individual tests were carried out during this stage. Apart from minor alteration and tweaks, Key Stage 1 also resulted in the creation of more significant improvements, including the creation of a foam-setting frame, and the customisation of a bandsaw machine for the cutting aspect of the process. The creation of these elements is covered in a subsection of this chapter.

The objectives for the Key Stage 1 tests were summarised as:

- **To identify and explore early key factors and variables in the system**
- **To identify and implement improvement to the system**
- **To establish a formal testing method and set up**

Following the Key Stage 1 tests, a second series of tests were undertaken, during which the system did not undergo any alterations. At this stage the system had reached the final development stage within the framework of this study. This series of tests were undertaken in order to accurately assess many aspects of the performance of the system, and therefore a constant, controlled set-up was needed to get accurate research data. Consequently, this stage, identified as: 'Key Stage 2 tests', employed empirical and quantitative research gathering methods.

The objectives for the Key Stage 2 testing included:

- **To test the repeatability (consistency) of the production output**
- **To test the accuracy of translating digital design data to the physical foam shapes**
- **To test the impact of the shape topography on the system accuracy.**
- **To test the durability of the system**
- **To test the system in the context of other furniture production aspects**
- **To establish the overall viability of the concept**

More than 100 tests were carried out during the two key stages, with tests labelled from 1 to 89 undertaken out as Key Stage 1, and tests labelled 90 to 110 carried out as Key Stage 2.

While a number of improvement and alterations were carried out during Key Stage 1, the testing situation and *general set-up* was relatively consistent for both of the testing stages. The testing situation and set-up will be outlined in the following subsection.

7.2.10.1 Test Situation and General Set-up

As the development of the foam RPT concept was done in consultation with the industry partner, MARK Product, the initial aim of creating an RPT system was that it that could be tested in an actual production context.

As has been previously highlighted, the initial series of tests were carried out while the system was still in the process of being fully established. At this early stage of testing it would have been premature to involve an industry collaborator, particularly as the system was still undergoing a number of alterations to improve its performance. During this test series it became increasingly clear that it would not be possible to develop the system to reach a level of maturity where real-life industry testing would be a realistic option. Consequently, all of the tests in both of the key stages were carried out by the researcher in the design workshops at Falmouth University.

The core set-up of the RPT system remained broadly similar for both of the key stage tests. This system consisted of four units: a computational control unit, a CNC pin setting unit, a mechanical RPT unit and a cutting unit. All of these units, again, consisted of several individual (and detachable) elements, but in the context of the testing process they should be considered as four complete units. The four units are illustrated in Fig. 95.

As the cutting of the foam was undertaken on a customised bandsaw, the core mechanical RPT unit had to be used as a separate, movable unit that would be attached to the CNC unit only during the pin setting stage. During this stage the RPT unit was fixed to the CNC unit via clamps with guide rails ensuring consistent and accurate positioning. The CNC unit was not equipped with limit switches or a fixed datum point, but a consistent datum location was implemented through the use of a small jig.

Fig. 95 The four foam RPT elements. From the top right corner: the CNC control unit, the CNC setting unit, the mechanical RPT unit and the cutting unit, photos: T. Jørgensen, 2014.

As previously described, the CNC unit was constructed as a classical Cartesian CNC set-up but operating on its side. The sledges with the pin units were positioned closely together with opposing pin tips at the end of the plywood rail. This arrangement enabled the pins in the pin unit that were facing the CNC system to be set from the back, with the pins being then set into position with the CNC system's pushing rod. As the pins in this set-up were facing each other, the pin being set in one unit would in turn push the pins in the other unit, with the result of the pins in both units being set at the same time (this process is illustrated in Fig. 97). This approach was not initially envisioned in this first construction of the system but discovered during pilot testing. The method effectively halved the time of the CNC operation needed to set the pins, which in any case was relatively quick, at an average of 2-4 minutes.

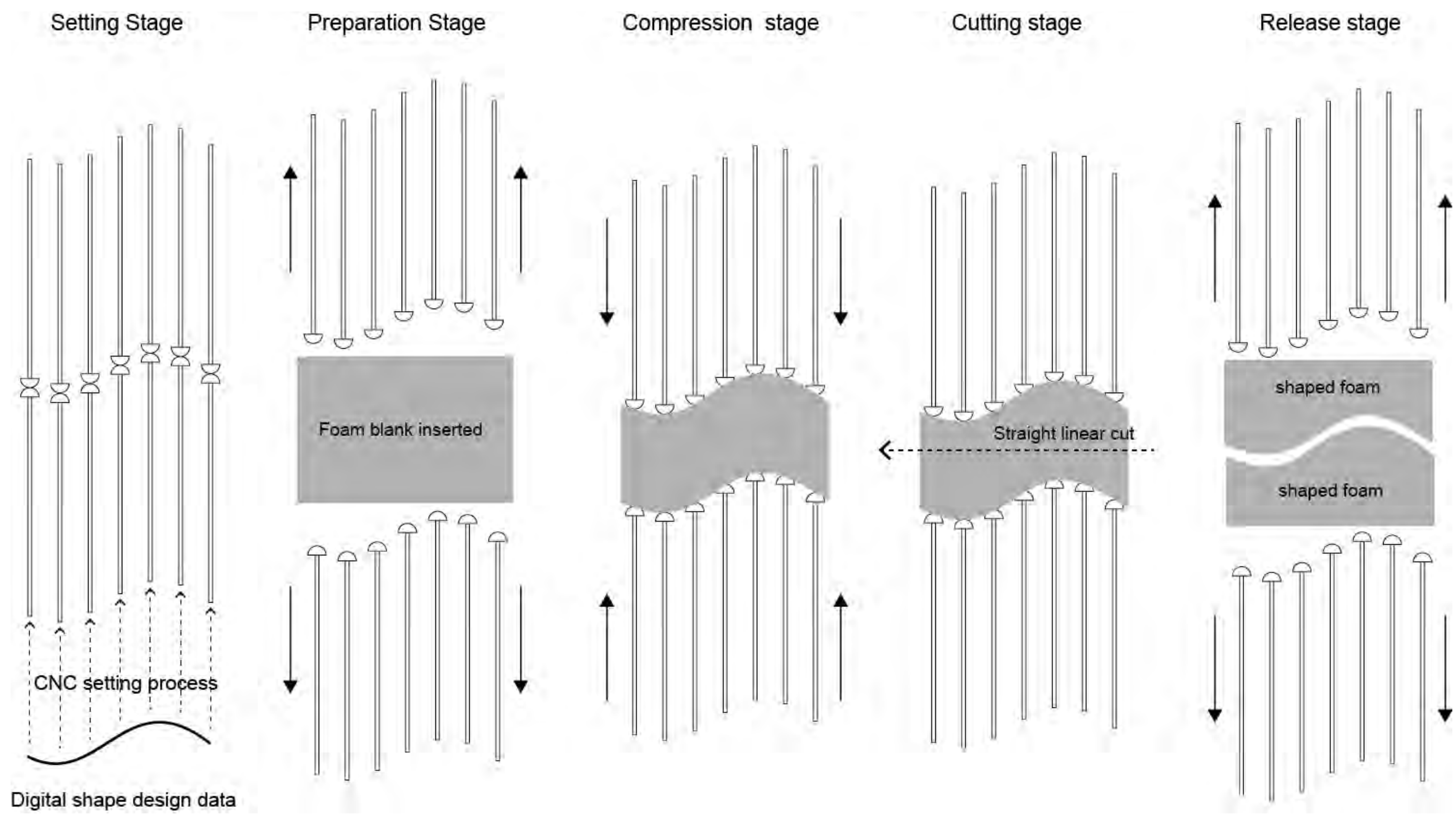


Fig. 96 Diagram illustrating the various stages of the foam RPT process.

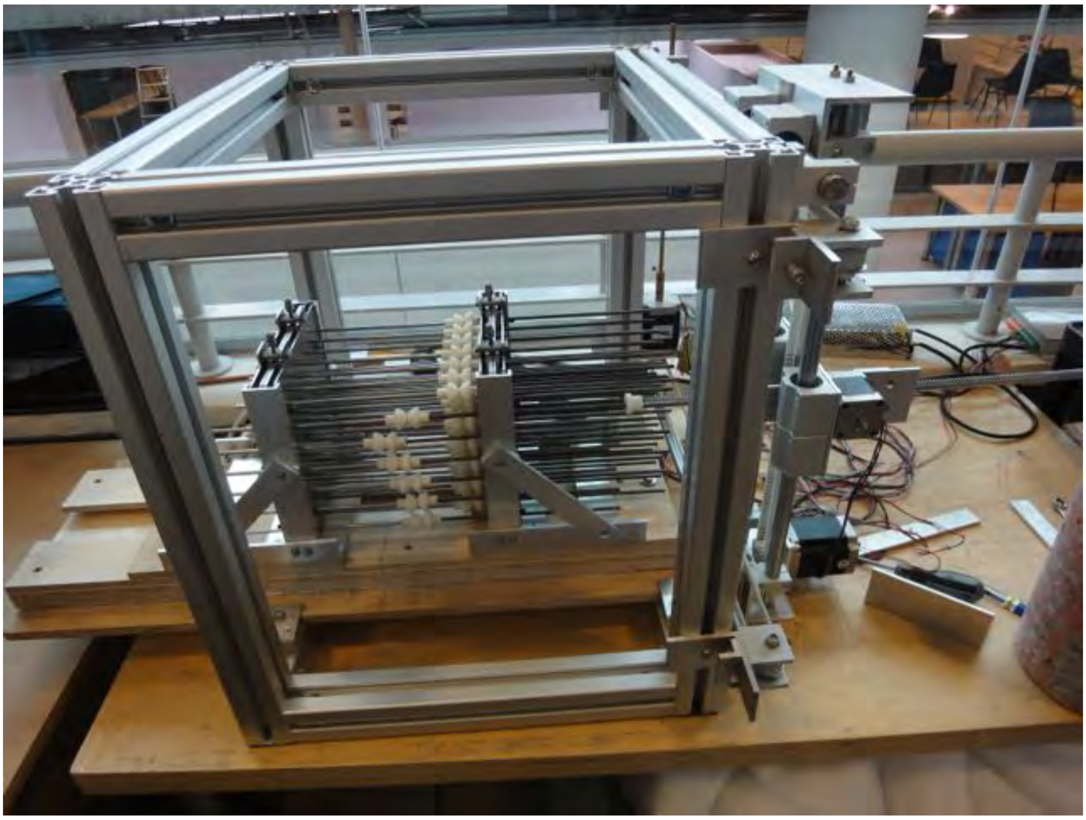


Fig. 97 Setting both sets of pins in a single operation via the CNC operated pushing rod. The opposing pin is being pushed into position by the other, photo: T. Jørgensen, 2014.

After the CNC setting stage, the pins were locked in position by turning the bolts that engaged the central locking plate. The mechanical RPT part of the system was then lifted out of the CNC setting frame, and the sledges with the locked pins could be slid apart ready to enable a foam blank to be placed between the pins. With one sledge firmly locked in position on the wooden rail the other sledge was manually pushed to compress the foam blank to the desired level. This sledge was then also locked, and the whole RPT unit was carried to a bandsaw to implement the cutting of the foam. This general approach was used throughout the testing session.

In order to have a number of different forms that could be used in the testing process the researcher developed a collection of five, three-dimensional shape designs in the Rhino software. These shape designs were also created in a physical form via 3D printing to enable the researcher to have tangible reference models to compare against the foam shapes. The size of these test shapes corresponded to the size of the pin matrix in the RPT system (150 x 150mm).

These shapes were designed to test the system's ability to handle a number of different topographies to test the flexibility (and limitation) of the system. The shapes were designed in Rhino as NURBS surfaces with a number and position of the control points to corresponded to the position of the physical pins in the RPT system. The shapes were designed with a *UV degree* of three, which means that the surface is *softly curved* in relation to the control points. The intention of this approach was to use shapes with a rate of curvature that corresponded to the kind of forms that could realistically be achieved in upholstery foam. Furthermore, the reason for aligning control points in the shape designs with the pin positions in the RPT matrix was to simulate the most realistic physical conditions within the virtual design environment. These five test shapes could, at any time, be edited further in the Rhino software by adjusting the location of the control points, thereby simulating the movement of a particular pin in the RPT device. In addition to the five shapes, a completely flat surface, labelled as shape '0', was also used in many of the tests as a *standard* to enable calibration and for checks for the accuracy of the system to be carried out.

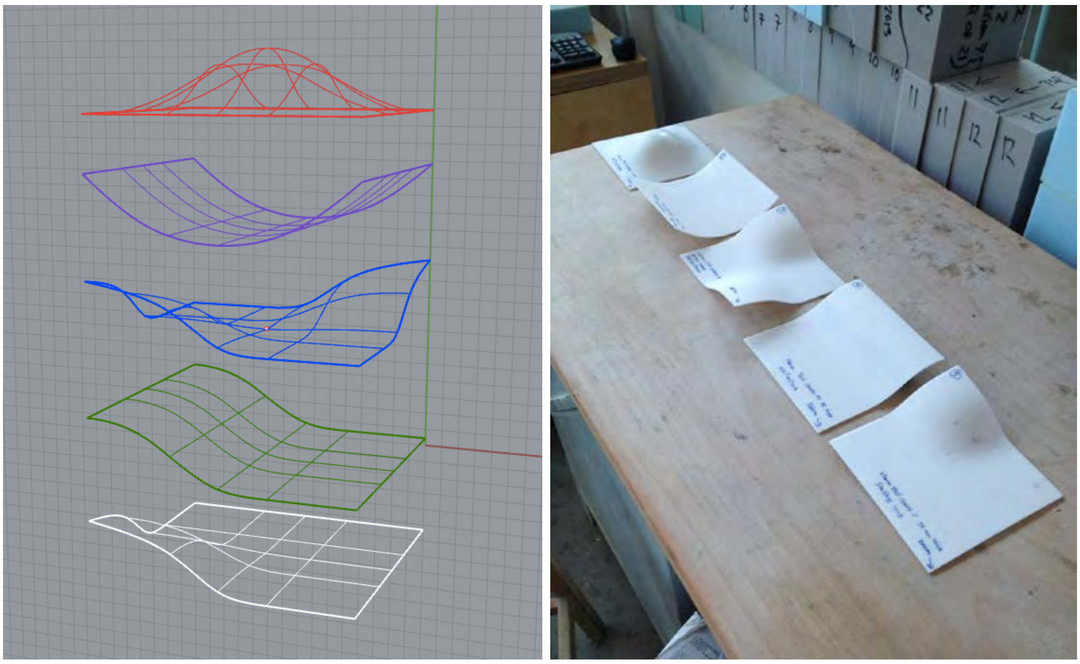


Fig. 98 The test shapes designed in Rhino and physicalized via 3D printing to aid visual inspection of the foam shapes, photo: T. Jørgensen, 2013.

The test shapes were also intended to test how the foam shaping method would cope with forms with curvature in various positions. Recognisable features were designed into these forms, with several of the forms being symmetrical. The rationale for this approach was to facilitate a way where any issues with the foam moulding system would be more obvious in regular geometries rather than in more random forms.

The height, or what could be described as the extent of the shape envelope of the test shapes, was somewhat limited by the inherent nature of the RPT set-up. As the straight cut of the bandknife blade always had to be placed between the opposing pin sets for the concept to work, the extremity of the shapes was limited by this situation. As a consequence, the test shapes were all designed to be within the same shape envelope, with the height of this envelope kept fairly consistent at 32-36mm. In the final test series, which is illustrated in Table. 1, (p 209) a uniform high of 32mm was used to maintain a consistency in the set-up so other factors and variables could be exposed.

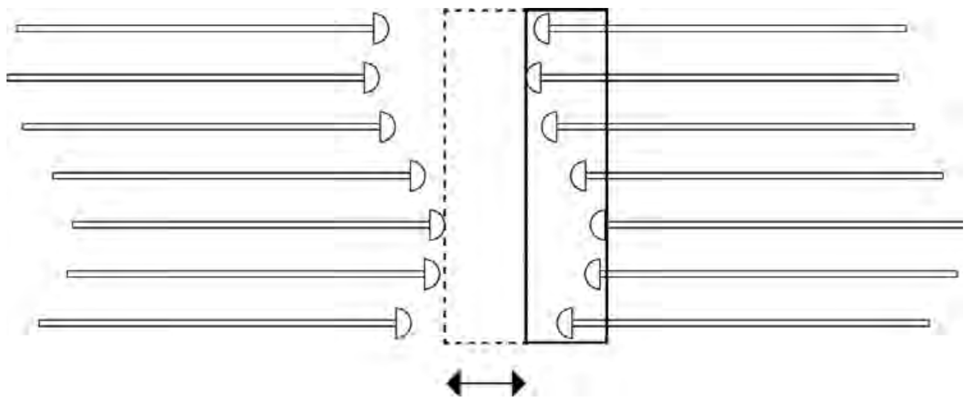
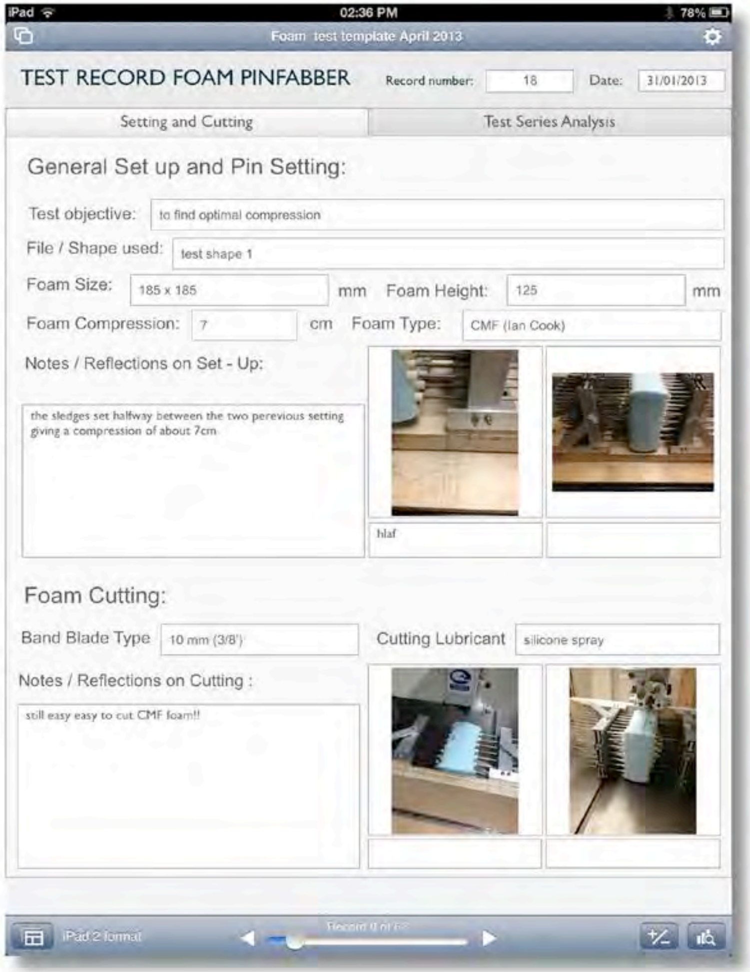


Fig. 99 Illustration of the extent of the system's inherent shape envelope.

To record the tests, the researcher developed an IOS enabled database template. This template, like all others used in this study, was created specifically for this investigation using the FileMaker Pro software. The template was formatted specifically for use on an iPad 2 tablet, which was mostly used during the testing of the foam RPT system. The IOS template for these tests was created with two main 'leaves'. The main leaf (titled 'Setting and Cutting') was again separated into two main sections, one concerning the set-up of the test and the other recording the process and immediate result. Both sections were facilitated via media holding fields in which documentation could be recorded in a variety of rich media formats (although most frequently images captured with the iPad's camera were used). The second leaf (titled 'Test Series Analysis') was designed to document and assess a small series of tests, and therefore generally only completed at the end of a test series rather than for each individual test entry.

Fields for textual notes and reflections were included on both leaves, but perhaps the text field that was most relevant was on the second leaf where analysis of the test sequence was recorded. A small media-holding field was positioned next to the text field to enable reflections to be recorded in audio format. Just like the other IOS templates created by the researcher this template was facilitated with dropdown menus and auto-fill content to aid an easy inclusion of circumstantial and frequently used details. The template is illustrated with an example entry in Fig. 100.



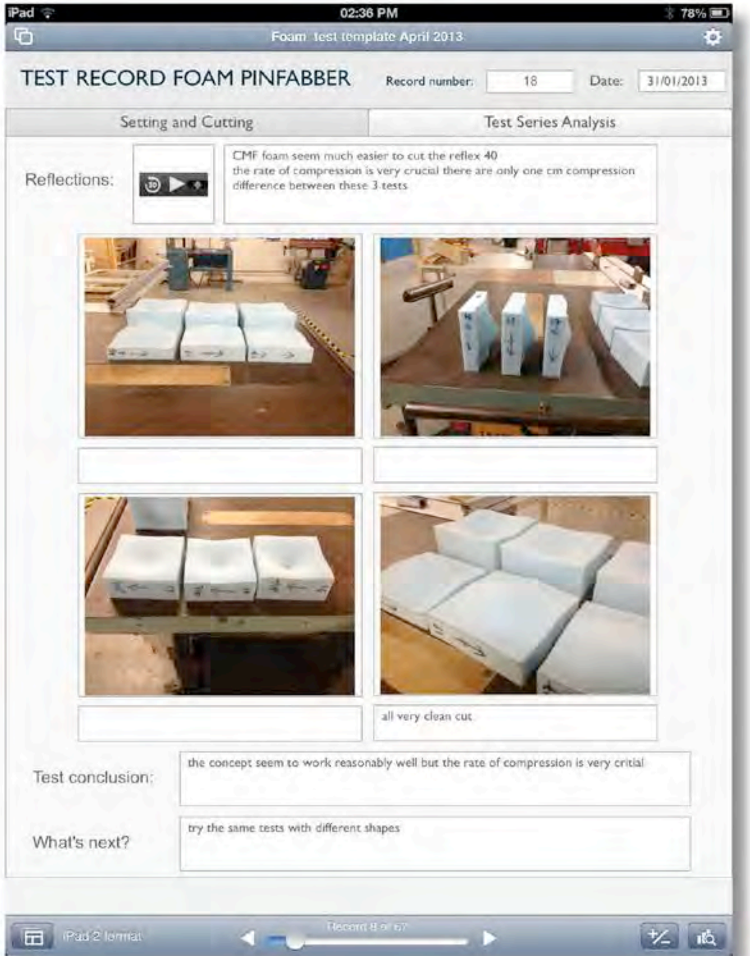


Fig. 100 The IOS database template created by the researcher to record the tests of the foam RPT system

7.2.10.2 Test Objectives, Test Results and Analysis

The following subsections will cover the objectives set out for the two testing stages of the foam RPT system. Each subsection provides an outline for the specific objectives, the issues involved and concludes with test results and analysis. It should be noted that these sections of analysis only relate to these specific objectives, and that reflections and analysis of the development of foam RPT system has been supplied in subsection 7.2.9, with overall reflection on this enquiry strand supplied in the discussion chapter.

7.2.10.3 Key Stage 1 Tests

The objectives for the Key Stage 1 tests included:

- **To identify and explore early key factors and variables in the system**
- **To identify and implement improvement to the system**
- **To establish a formal testing method and set-up**

These objectives are covered in detail in the following subsections. A rationale for each of the objectives is supplied with a description of the work carried out in response.

- **To identify and explore early key factors and variables in the system**

Addressing this objective was actually a part of defining the testing structure. Consequently, it was one of the first objectives that had to be addressed in the testing phase. Identifying key factors and variables in the system were also needed in order for the researcher to design the IOS database template that was used to record the tests.

The task of identifying some of the early variables that could be subject for further investigation were done within the very early explorations of the functional RPT system. These explorations, while still fairly primitive, were sufficient in providing some indication of the factors that would be of relevance to explore further in the tests (and therefore also needed to be included as specific fields in the IOS template). Some of the early variables and factors were identified in relation to the overarching objective. The breakdown of this objective is provided below:

- **To identify and explore early key factors and variables in the system**
    - **The cutting aspect**
    - **Foam types and characteristics**
    - **The foam compression levels**

These key factors and variables will be described and discussed in detail in the following subsections.

- **The cutting aspect**

One of the initial variables to be identified in the RPT system concerned the actual cutting of the foam. While this aspect could perhaps be seen as a relatively minor element in the overall foam shaping concept, it still constitutes a critical moment were the foam is actually formed according to the shape design. Prior to the Key Stage 1 tests the researcher had only explored this process during very crude explorations with an electric breadknife as the cutting tool. As previously mentioned, the researcher was aware of professional foam cutting tools, such as the Bosch GCG 300, which is used as a hand operated cutting tool by many smaller upholstery foam suppliers.

As a part of the fieldwork and scoping activities of this study the researcher undertook several visits to a local foam company (Cook, 2014). During these visits it was observed that a large, specialist, bandknife machine was used to cut the slabs of foam (see Fig. 105). The principle used for this machine is almost identical to that of a bandsaw, although, instead of using a toothed blade a sharp toothless bandknife blade is employed. The researcher concluded that the use of such a machine would present the best option as a cutting device for the foam RPT concept. Bandknife machines are made as specialist machine tools for cutting textile, leather or paper. However, a standard bandsaw machine can also be fitted with a bandknife blade and thereby used to cut the materials mentioned above. The researcher acquired various bandknife blades for a bandsaw machine in the university's workshop to enable this machine be used to implement the cutting element of the foam RPT concept.

Initially, the integral *tilt* action in the foam RPT sledge system (which was developed as a concept during the early prototyping session (see subsection 7.2.2) had been intended to pivot the pin units (with the compressed foam sandwiched between the pins) through the operating bandknife. However, initial tests with this approach resulted in a highly textured surface on the foam. To avoid this texture the pin units were tilted prior to being pushed through the bandknife blade. This approach produced much better results, and the method of tilting the pin units prior to cutting was from then on employed in all the tests (see Fig. 76)

The particular bandknife machine employed by the local foam company was fitted with a large rolling platform to aid a very consistent and straight cut in the foam. Initially the researcher tried to emulate this approach by sliding the RPT unit along a guide rail on the bandsaw machine; a method which initially produced some reasonable results.

Initial explorations had also highlighted other factors in relation to cutting, in particular, the way that the bandknife blade would travel through the foam. Apart from specialist applications, such as the production of acoustic foam, upholstery foam is generally not compressed during the cutting process. Even under standard cutting conditions the elastic characteristic of upholstery foam carries its particular fabrication challenges as the foam can easily distort during the cutting process. This issue is potentially further intensified when the foam is in compression. In early explorative tests the researcher observed how the compressed foam would *grip* the bandknife resulting in the foam almost being pulled off the pin units during the cutting process. This was a significant issue with a particulart type of foam (Reflex 40), which seemed to grip the blade to a much higher degree than other types of upholstery foam.

The researcher concluded that this issue could have a serious impact on the feasibility of the overall concept. To address this problem it was proposed that a number of options in this variable were to be investigated, including: the bandknife blade width, use of lubricants and potentially also the rate of compression in the foam. Specific fields were included in the design of the IOS template, so details of these factors could be easily recorded from the tests.

Three different bandknife blades in widths of 3/8” (10mm), 1/2” (12.5mm) and 3/4” (19mm) were initially acquired. The aim was to establish the best level of performance in terms of the cleanest cut, with the lowest amount of *grip* or *pull* on the foam during the cutting. However, initial tests seem to indicate little apparent difference in the performance of the blade width. Silicone lubricant spray was also tested, which appeared to significantly alleviate the problem with the foam *gripping* the blade. The silicon was sprayed generously on the running blade prior to each cut. WD 40 was also tested as a cutting lubricant but did not appear to perform as well as the silicone.

One aspect that significantly improved cutting was the sharpening of the band blade. The researcher was unaware that the specialist bandknife machines normally include a continual blade sharpening device and therefore the blade manufacturers generally supplies the bandknife blades semi blunt to prevent damage to the edge in transport. Unaware of this situation the researcher used unshaped blades during many of the initial tests. This incident perhaps highlights some of drawbacks for innovators operating in sectors they are unfamiliar with. In response to this situation, the researcher developed a simple procedure of sharpening the bandknife blade manually while it was running on the bandsaw machine. After a series of tests exploring the variable in the cutting process a best practice method was arrived at. This method consisted of the use of a 10mm blade, which would be sharpened after 5-6 cuts. The use of silicone lubricant spray on the blade prior to each cut was also adopted as a standard.

Another key factor in relation to the foam cutting was the position of the cut in relation to the two opposing pin units. In this situation, the aim was to establish a *constant* rather than a *variable* factor. The strategy to achieve this constant was to position the cut at an equal distance between the pin units as accurately as possible. In response to this issue the researcher made a number of very fine pencil marks on the plywood rail to aid the positioning of the bandknife blade before the cut. It took a number of attempts to establish the most accurate position of this cutting line.

It is relevant to note that the accuracy of lining up the cutline between the pin units was discovered to be much more critical than initially expected. This is related to the nature of the process where the foam is cut while being compressed over 50%. After the cut, when the foam is released from the compression it expands back to its normal size and any inaccuracies doubled. This situation required the researcher to carry out multiple alterations and tweaks to the system to achieve a higher level of accuracy.

- **Foam types and characteristics**

With the many technical challenges related to the construction and operation of the RPT unit, it could easily be overlooked that it is the particular material characteristics of upholstery foam which is at the core of the manufacturing concepts in the foam RPT system. These material characteristics can be summarised as a particular combination of elasticity and compressibility. The importance of the material characteristics of the moulding medium is a recurring theme this overall study and reflections on this aspect more widely are provided in the discussion chapter (subsection 9.1.3).

Prior to this study the researcher had little knowledge of the range of furniture foams commonly used. It was expected that a wide range of foams would be available to investigate in the testing phase of the system. However, fieldwork and scoping activities revealed that there were only a relatively narrow range of options.

Through the interaction with MARK Product, the foam RPT system was developed with the intention of shaping foam that would be used in a furniture application, particularly with the intention of developing a seat or stool. Foam used for such applications clearly needs to have a level of softness that is comfortable to sit on. This particular application reduced the range of appropriate upholstery foam to only a few available options. Following advice from suppliers the researcher selected two types of foam that were considered to be the most suitable options for this application.

One of the foams selected was the Reflex 40 type, which is a high quality foam that provides a very good level of comfort as well, and a very high level of durability. This type of foam is typically light grey in colour. As a cheaper alternative to the premium Reflex 40 product, a lower grade foam known as Combustion Modified Foam (CMF) was also selected to be a part of the testing session. CMF is usually light blue in colour, and provides a similar level of comfort to Reflex 40, but does not have the same level of durability.

Fig. 101 Foam slabs stored in Ian Cook and Sons' workshop in Roche near St Ives, Cornwall, photos: T. Jørgensen, 2012.

To be able to apply sufficient compression levels, relatively thick foam blanks had to be used for the RPT system to work. Upholstery foam is manufactured in very large blocks that are then sliced into slabs of a range of standard thicknesses. The thickest standard foam slab that is readily available is known as a '5 inch' slab. The accuracy of this type of foam appears to somewhat variable, with the researcher experiencing thicknesses from 128mm to 133mm. While the RPT system operates with a 150 x 150mm matrix of pins, the foam blanks used in the testing process were over-sized to prevent the foam from sliding off the perimeter pins during the compression stage. Usually blanks around 185 x 185mm was employed, which is a size that enables the foam block to overlap the pin matrix by approximately 17.5mm on all sides.

The issue with accuracy and consistency in the foam shapes created on the system is the subject for analysis in specific objectives in a later subsection, but these issues also have some relevance in regard to the foam types, and therefore this issue is also relevant to discuss in this section.

At various stages during the early tests one particular type of foam appeared to perform better than another in terms of producing an accurate representation of the set pin forms. However, when the shapes were examined more closely, little obvious difference in the performances could be detected. Equally, the particular tests which seem to indicate this situation were carried out at an early stage during the Key Stage 1 testing phase when the overall set-up was still being refined, and a number of inaccuracies in the system were still in the process of being ironed out.

In conclusion, and based on both key stage tests, the two foam types seem to perform broadly similar in terms of the accuracy and consistency in the shapes produced, and therefore not relevant as a significant variable in the system.

- **The foam compression level**

The impact of the level of compression on the foam blanks was, right from the initial explorations, considered to be a core factor in the entire foam RPT production concept. In the early prototyping experiments the researcher had experienced how applying various amounts of compression to the foam would change how the production concept would reproduce the shape. A low compression rate would result in foam surfaces that would be shaped less than the forms set in the pins units, while a very high compression rate would result in foam surfaces that had more extreme shapes than the ones used to mould the foam. Only a balanced compression rate would produce shapes that most closely resembled the shape set in the pin units.

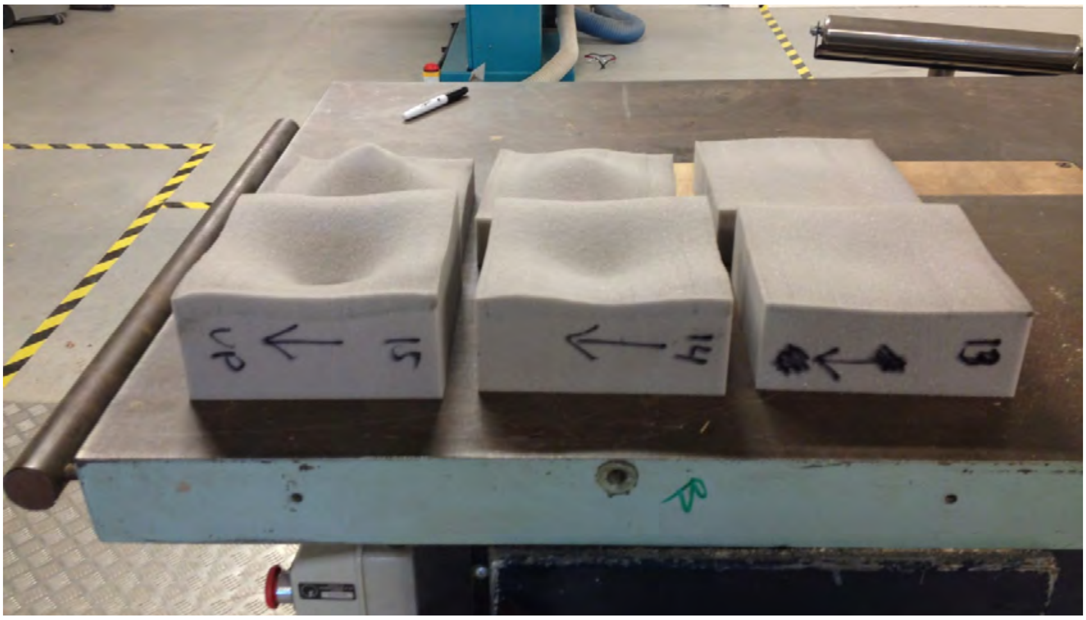


Fig. 102 The impact of different levels of *compression* on the shape, test no 15 - 62%, test no 14 - 54% and test no 13 - 39%. Test number 15 is significantly deformed due to 'over compression' of the foam. The same pin setting shape (test shape 2) was used for all these tests, with only the compression rate altered, photo: T. Jørgensen, 2013.

Initial tests attempted to establish a generic compression rate by applying a foam compression ranging from 39-62%. Again, these tests showed that the cut foam shapes could be enhanced beyond the shape that was set in the pin unit by increasing the rate of compression. But while shapes could be enhanced by increasing the compression, the accuracy of the resulting forms would also diminish. The result of these tests indicated that a compression rate of around 57% produced the most balanced results.

The various compression tests were initially carried out by placing marks on the plywood rail recording the distance of the compression in centimetres. But these tests also exposed practical difficulties in the manual operation of compressing the foam in accordance to the marks on the rail. It proved difficult to reliably push the sledge to a particular mark in the rail. As a remedy, sticks to define the compression rate were produced in aluminium profiles (a later set was laser cut in clear acrylic). These sticks ensured that the sledges would be pushed together to a defined distance, thereby ensuring a consistent and accurate compression rate in the tests.

Fig. 103 Aluminium sticks to ensure consistent and accurate compression rates being applied to the foam during the testing. This is also illustrated in Fig. 104, photos: T. Jørgensen, 2014.

In trying to identify how the level of compression was absorbed in the foam, the researcher carried out a series of tests. In these tests the pins were set to produce a completely flat surface (shape 0). Prior to the foam blanks being applied in the system, the researcher marked them with thin lines in order to observe how consistently the foam would compress. These tests seem to indicate some variation in the way that the foam absorbs the compression. The researcher observed that the straight lines (placed with intervals of 25mm or 15mm) would be shown to *wobble* somewhat when the foam was compressed. This finding indicates that the compression in the foam was not entirely constant throughout the foam, but varied according to the density and elasticity of certain sections of the foam. The impact of this inconsistency on the performance of the system is discussed in the subsection analysing the Key Stage 2 tests.

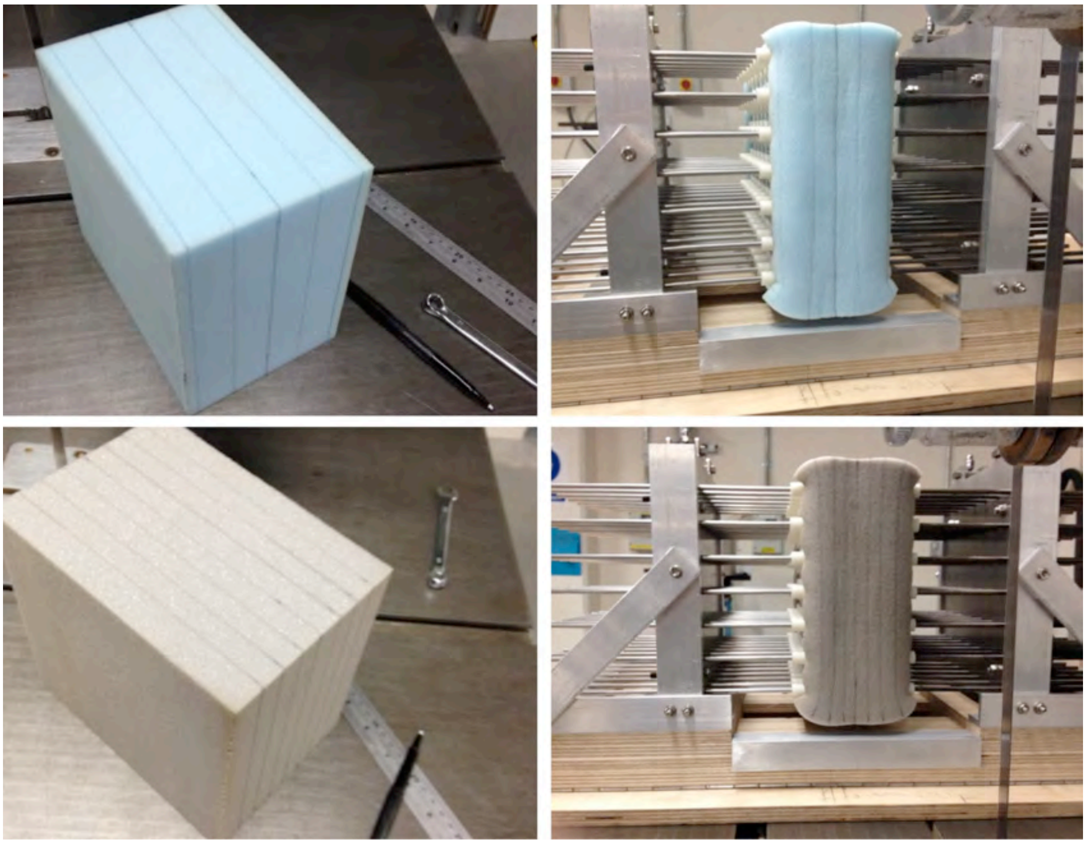


Fig. 104 Testing the way that foam compresses through lines drawn at regular intervals on the foam, photos: T. Jørgensen, 2013.

As the testing process progressed there were indications that there were issues in terms of the system's ability to consistently reproduce shapes. While the researcher tried to eradicate issues in the mechanical parts of the system that might cause these repeatability issues, tests were undertaken to investigate ways of *preparing* the foam blanks to elevate this issue.

The researcher considered that methods of pre-softening the foam could potentially produce more consistent results, and a couple of approaches were tried with this approach. With the foam placed in between the pin units several pre-compression pushes were employed to *warm up* the foam before full compression was applied. Other tests were carried out where the foam blanks were pre-heated to about 35ºC before being used. However, none of these tests appeared to indicate any significant improvement.

While a 54-57% compression rate was adopted as producing the most accurate forms overall, this figure was still a compromise. This rate of compression would generate foam shapes, which dependent on the particular topography of the design, would be more or less accurate in relation to the digital design input. As is further indicated in the results from the Key Stage 2 tests, further work is still needed to improve this issue.

- **To identify and implement improvements to the system**

Many of the initial tests carried out on the foam RPT system indicated issues in relation to the shape accuracy in translating digital designs to the foam shapes, and also the consistency of the output of the system, i.e. the repeatability of the foam shapes from the same pin setting.

The researcher initially considered the main cause of these issues was primarily due to inaccuracies in the construction of the system. Throughout the Key Stage 1 tests the researcher continuously implemented improvements and alterations to the system in an attempt to achieve a better performance. Most of these improvements took the shape of fine-tuning and adjustments, but some more significant improvements were also undertaken. These improvements concern the construction of a foam-setting frame and fitting a bandsaw machine with a rolling table to improve foam cutting. As previously mentioned, the researcher had observed at the local foam company (Cook, 2014) how a specialist bandknife machine with a rolling cutting table appeared to produce very accurate and consistent cuts in the foam slabs. It was concluded that changing the foam RPT system to include such a cutting table could potentially eradicate some issues concerning consistency and inaccuracy.

Fig. 105 Specialist foam cutting bandknife machine with a rolling cutting table as used by Ian Cook and Sons, photos: T. Jørgensen, 2012.

The researcher implemented such a rolling table with a bandsaw on a smaller scale. The rolling table applied to the bandsaw was constructed with discarded aluminium profiles that were bolted on to the side of the bandsaw table. Sets of shower screen rollers, bought cheaply on eBay, enabled the movement of the table, while a piece of plywood was used as the table bed. While the alteration was implemented quickly, a high degree of care was taken to insure that the improvement did not lead to further inaccuracies in the system. Despite a negligible manufacturing cost (about £10-15) the rolling table enhanced the cutting process of the system significantly. By using equipment and materials readily to hand, and at low cost, the approach used in converting this bandsaw with a rolling bed followed the approach used in many other aspects of this study, which relates to working practices (such re-appropriation of off-the-shelf technology, development through prototyping rather than pre planning) — aspects that are typically associated with the current subcultures of independent innovators (see subsection 5.1.2).

Fig. 106 Constructing the rolling bed for the bandsaw, photos: T. Jørgensen, 2013.

The positioning of the foam blank in between the pin units was another aspect that was identified as a potential source of inconsistency in the system. Difficulties had been observed in holding the foam in a fixed position when moving the pin units together to apply compression to the foam. The spiked pin tips had been designed to prevent this issue, but their design was still not sufficient enough to elevate this issue entirely.

In response, a frame to hold the foam blanks in a consistent position during the compression stage was proposed. The requirement of the foam-setting frame did present challenges in terms of the construction. The frame had to support the foam on all four sides while still enabling the pin units to be brought together to apply pressure on the foam. After locking the system with the foam in compression, the frame had to be removed in order to enable the bandknife blade to cut the foam between the two pin units. This particular feature was achieved by making a separate base to the frame that could be removed separately after the main frame was lifted off in preparation for the cutting process (see Fig. 108)

The frame was fabricated by using the university's in-house laser cutter to cut sections in 6mm clear acrylic, which was then assembled with glue. While the researcher used university facilities in this case, laser cutting equipment is now so widely available that an innovator without an university affiliation would very easily access such fabrication capabilities.

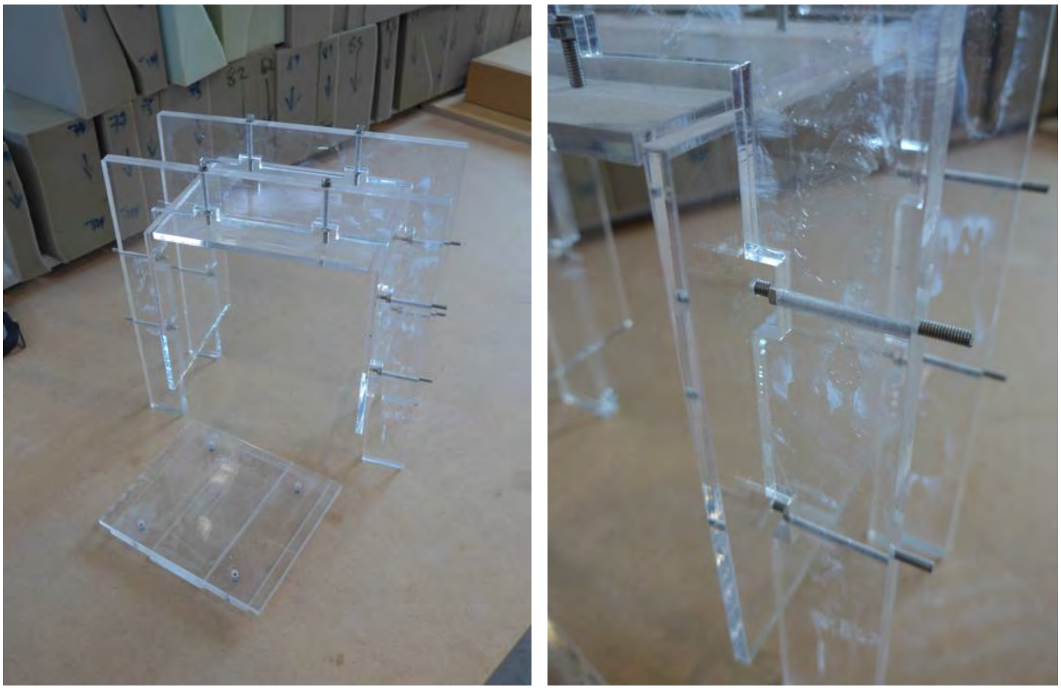


Fig. 107 The Perspex foam-setting frame with adjustable sides to compensate for inconsistencies in the size of the foam blanks, photos: T. Jørgensen, 2014.

In use it was observed that there was an unexpected effect when using the frame. During the process of compressing the foam blanks between pin units, the foam would have a tendency to bulge out of the base of the frame and thereby lift the frame up.To prevent this from happening heavy weights were placed on top of the frame during the compression stage. The weights could be removed as soon as the pin units were locked in position (see Fig. 108).

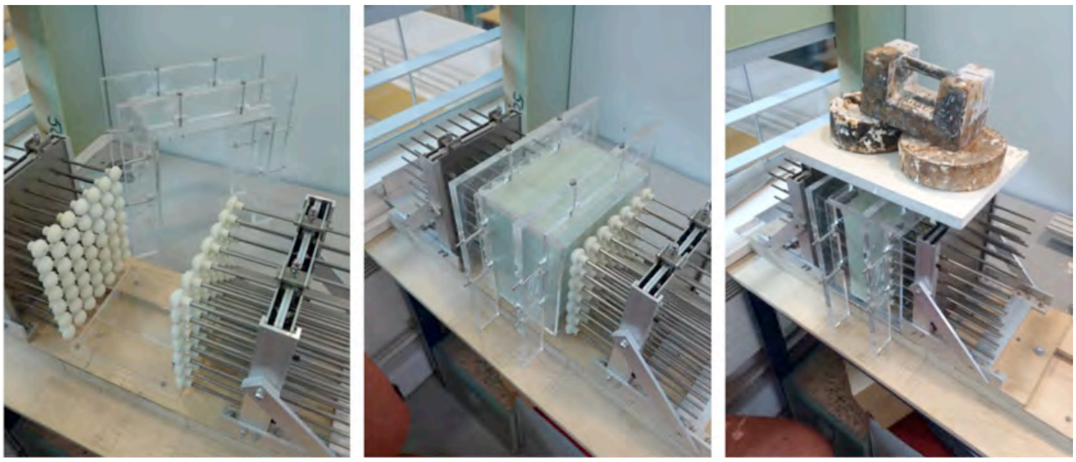


Fig. 108 Illustration of the use of the Perspex foam-setting frame, photos: T. Jørgensen, 2014.

The frame for setting the foam did appear to provide some improvement in the performance of the system, but it did also add another level of complication and could be rather cumbersome in use, and for this feature to be a part of a viable and effective production system further improvements would be needed.

- **To establish a formal testing method and set up (in preparation for the Key Stage 2 tests)**

Over 80 tests were carried out on the system during Key Stage 1 using the same basic testing situation and general set up that was outlined at the start of this subsection. However, as previously highlighted, the majority of these tests were carried out while the researcher was still undertaking significant adjustments and improvements to the system. These tests were still recorded using the IOS database template, but the results were only assessed visually and accurate measurement of the foam shapes were not recorded.

In order to more accurately assess the performance of the system, a series of tests was needed to provide a clear picture of the performance of system and in response, the Key Stage 2 tests were instigated. This testing stage consisted of 21 tests undertaken with consistent data gathering conditions to achieve the most accurate data.

In preparation for Key Stage 2 tests the system was checked for any misalignment and inaccuracies to ensure that this series of tests would provide the best possible basis of an assessment of the system's performance. In addition to the use of the IOS database template, an accurate method of measuring the foam shapes was also established using the CNC unit from the foam RPT system, but fitted with the digitising probe developed by the researcher and set-up as described in sub section 7.2.8.

The measurement pattern employed with the digitising probe used nine data sampling points. The nine sampling points were distributed at 75mm intervals as an equal matrix within a 150 x 150mm square, which corresponded to the size of the pin matrix in the RPT system, rather than the 185 x 185mm foam blank size (a size resulting in the 17.5mm border to ensure that the foam blanks did not slide off the perimeter pins during the compression stage). The points sampled through the digitising process were recorded as simple coordinate numbers which could be imported into Rhino 3D as a point cloud (see Fig. 111). This point cloud could then be analysed accurately in relation to the corresponding digital design data of the test shape which was used to set the pins in the RPT system. This process ensured that the physical output (the foam shapes) could be measured accurately against the digital design data.

It is relevant to note that in order to eliminate errors that stemmed from slight misalignments of the cut of the bandknife blade, the point clouds were grouped and centrally aligned with the digital test shape design. As the sampling points were all collected with the same 75mm intervals, and the recording of the foam shapes carried out while these were all aligned on the digitising platform, only the Z-axis provided data which was relevant to the testing process. Fig. 109 to Fig. 112 illustrates the process of collecting the data gathered from the physical foam shape through the use of the digitising probe.

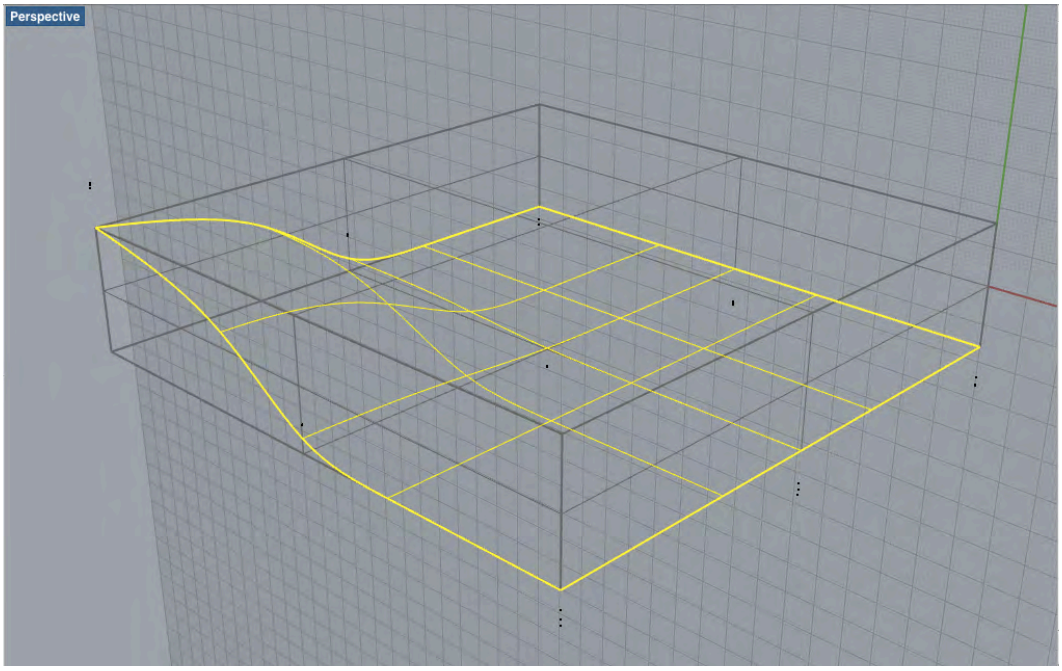


Fig. 109 The digital design data (shape 5) aligned in bounding box, with Z-axis datum located at the centre of the box.

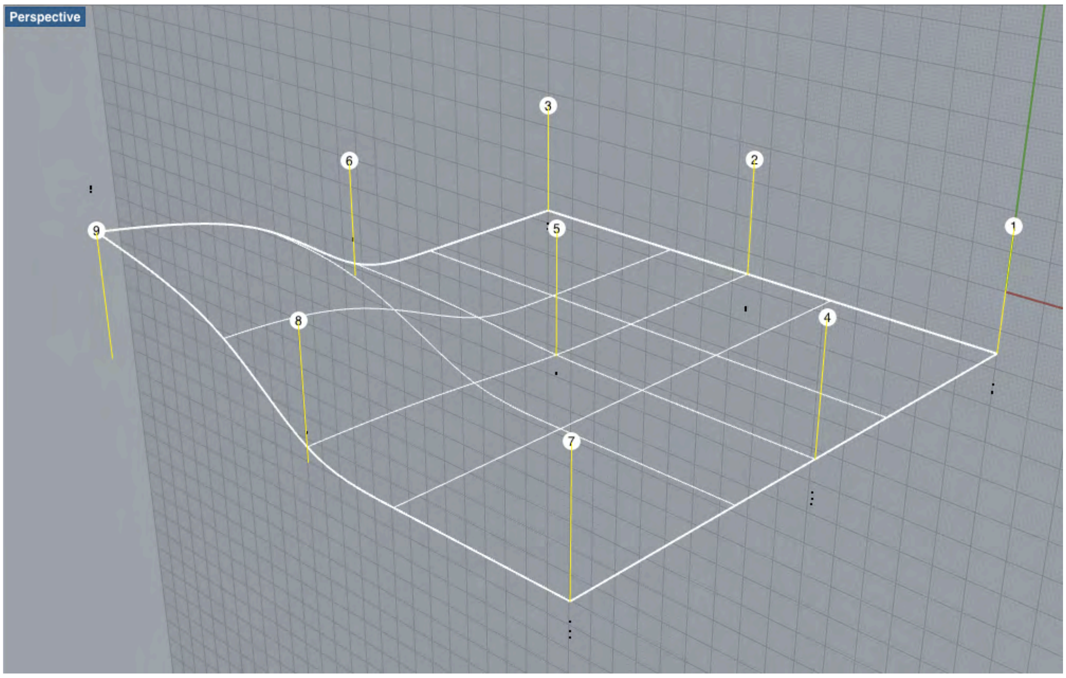


Fig. 110 The positions of the nine data sampling locations in relation to the shape design.

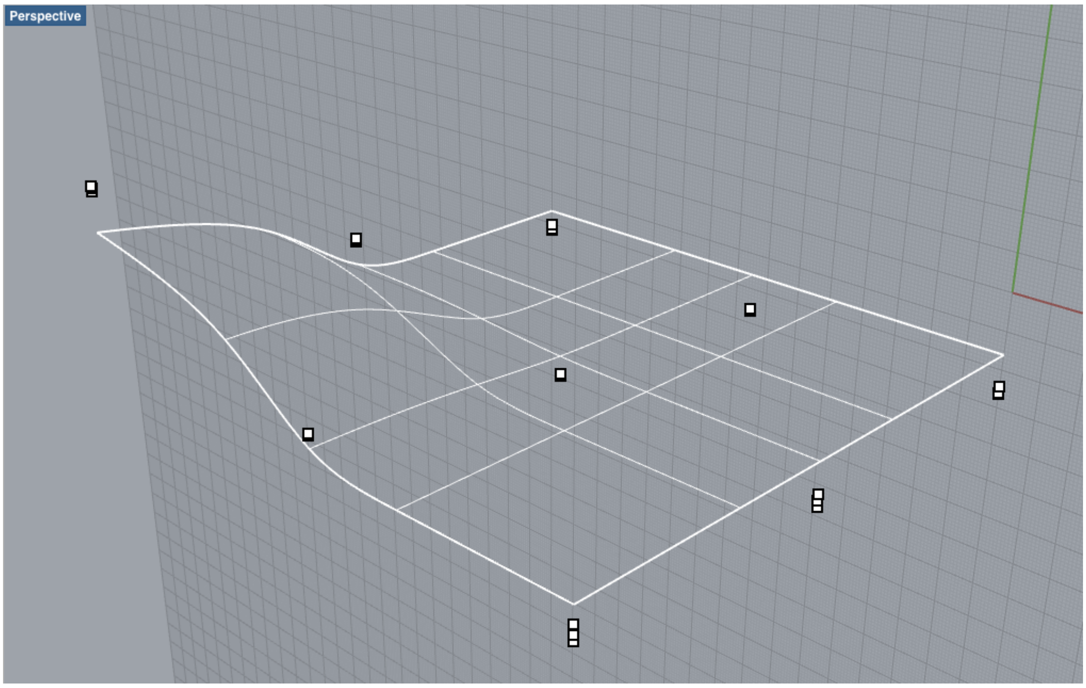


Fig. 111 Cluster of points sampled from three foam shapes using the digitising probe.

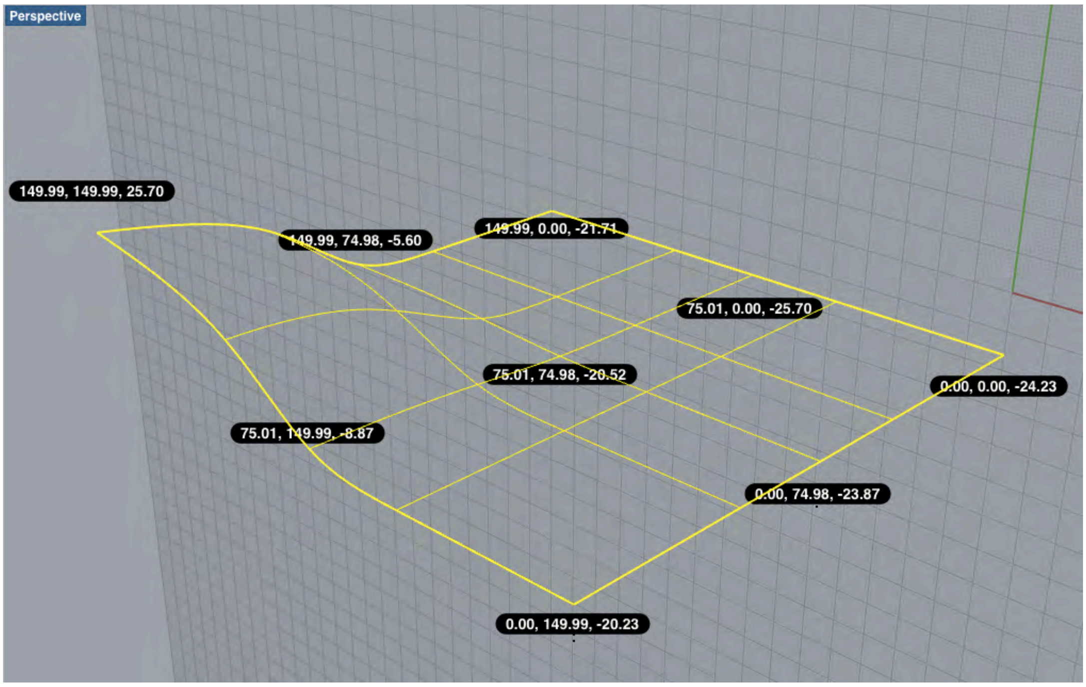


Fig. 112 Digitised point locations gathered from one of the foam shapes, expressed in co-ordinate numbers.

7.2.10.4 Key Stage 2 Tests.

The objectives for the Key Stage 2 testing included:

- **To test the repeatability (consistency) of the production output**
- **To test the accuracy of translating digital design data to the physical foam shapes**
- **To test the impact of the shape topography on the system accuracy**
- **To test the durability of the system**
- **To test the system in the context of other furniture production aspects**
- **To establish the overall viability of the concept**

The Key Stage 2 series of tests (labelled from 90 to 110) utilised all of the five test shapes. Additional tests were also undertaken using a completely flat surface (shape 0). These tests were carried out over two consecutive days with an entirely consistent set-up using CMF foam blanks sized approximately 185 x 185mm by 125mm thick. A compression rate of 57% (80mm) was used, and a 10mm wide bandknife blade lubricated with silicone spray was also used.

The entire test series was carried out using the Perspex foam-setting frame to insure a consistent and controlled positioning of the foam blanks (tests 92-95, were omitted from assessment as these were carried out without the Perspex frame).

Each of the digital shapes was set in the pin unit using the now firmly established setting procedure.

Each of the shape designs was only set once in this test series, but three foam cutting tests were carried out with each of these shapes before the pin matrix was re-set to undertake another series of tests on a different shape. These three repeated tests provided data for assessing the system's capacity for producing consistency in the output. Identifying the rate of consistency with the system also provided a better basis for assessing the accuracy of the system in translating digital design data into the foam shapes.

Fig. 113 The pieces from the last test series all laid out for inspection and analysis, photos: T. Jørgensen, 2014

All the tests were recorded using the IOS template, with each of the series of three tests recorded through digital images and assessed visually as a group. The database template was also used to record textual notes and audio recordings of the researcher's reflections on each of the group of tests. Following the stage of visual evaluation, all of the tests were measured using the digitising probe.

All of the data from the points sampled from the foam shapes were collected in a spread sheet illustrated in Table. 1. In this table the repeatability (consistency in producing multiple copies from the same set pin shape) as well as accuracy in relation to the digital design data input was calculated from numerical data.

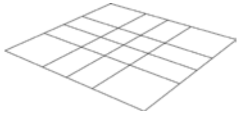
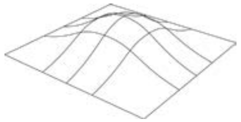
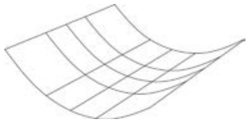
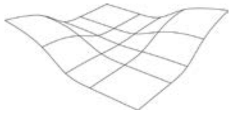
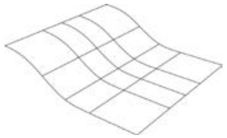
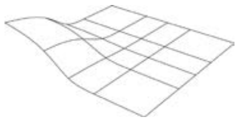
shape no	Test shape visualization		Digitised sampling points in Z axis only (all numbers in millimeters)									Average (in)accuracy in **mm** per test shape	Average (in)accuracy in **%** per test shape	Average (in)consistency range in **mm** from 3 tests	Average (in)consistency range in **%** from 3 tests	Minimum (in)consistency range in **mm** from 3 tests	Maximum (in)consistency range in **mm** from 3 tests
			1	2	3	4	5	6	7	8	9						
		Control points position	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
		Test 90	-1.64	-1.81	0.34	0.02	-4.25	-1.14	3.09	0.71	4.24	**1.92**	**1.5%**				
0		Test 91	-2.46	-1.55	1.33	-0.04	-2.79	-3.5	-0.96	-0.4	3.5	**1.84**	**5.7%**				
		Test 92	0.23	0.28	1.21	-1.61	-2.29	-0.58	1.7	-0.64	2.29	**1.20**	**3.8%**				
		(in)consistency range	2.69	2.09	0.99	1.63	1.96	2.92	4.05	1.35	1.95	**3 tests % average**	**3.68%**	**2.18**	**1.7%**	**0.99**	**4.05**
		Control points position	-16	-16	-16	-16	16	-16	-16	-16	-16						
		Test 96	-15.46	-9.2	-12.16	-13.17	15.46	-12.79	-14.28	-10.46	-12.73	**3.14**	**2.5%**				
1		Test 97	-14.52	-8.06	-11.12	-12.26	14.52	-12.5	-13.04	-10.19	-11.05	**4.08**	**3.3%**				
		Test 98	-15.63	-8.19	-12.74	-12.48	15.63	-12.54	-11.37	-7.28	-7.9	**4.47**	**3.6%**				
		(in)consistency range	1.11	1.14	1.62	0.91	1.11	0.29	2.91	3.18	4.83	**3 tests % average**	**3.12%**	**1.90**	**1.5%**	**0.29**	**4.83**
		Control points position	16.00	-16.00	16.00	16.00	-16.00	16.00	16.00	-16.00	16.00						
		Test 99	12.58	-17.35	15.13	17.35	-17.03	15.08	15.17	-14.99	14.11	**1.41**	**1.1%**				
2		Test 100	17.61	-19.96	21.56	21.1	-21.56	18.41	18.67	-18.65	19.9	**3.71**	**3.0%**				
		Test 101	16.48	-20.7	21.7	21.55	-21.7	17.06	19.16	-17.26	19.66	**3.47**	**2.8%**				
		(in)consistency range	5.03	3.35	6.57	4.20	4.67	3.33	3.99	3.66	5.79	**3 tests % average**	**2.29%**	**4.51**	**3.6%**	**3.33**	**6.57**
		Control points position	16.00	-12.33	-16.00	-12.33	-16.00	-12.33	-16.00	-12.33	16.00						
		Test 102	20.93	-18.19	-24.65	-8.67	-20.15	-15.06	-22.33	-10.33	24.65	**5.22**	**4.2%**				
3		Test 103	21.33	-19.94	-26.25	-7.85	-21.07	-17.65	-26.09	-11.83	26.25	**6.54**	**5.2%**				
		Test 104	24.58	-15.82	-23.63	-5.88	-17.29	-14.27	-25.49	-9.56	25.49	**5.68**	**4.5%**				
		(in)consistency range	3.65	4.12	2.62	2.79	3.78	3.38	3.76	2.27	1.60	**3 tests % average**	**4.65%**	**3.11**	**2.5%**	**1.60**	**4.12**
		Control points position	-16.00	-13.58	16.00	16.00	-13.58	-16.00	-16.00	-13.58	16.00						
		Test 105	-31.44	-14.47	31.38	32.25	-15.70	-32.25	-26.77	-12.63	29.58	**10.18**	**8.1%**				
4		Test 106	-32.21	-15.01	30.41	32.21	-15.07	-31.43	-26.64	-13.34	27.91	**9.77**	**7.8%**				
		Test 107	-33.51	-16.39	31.78	33.51	-16.48	-33.50	-29.36	-14.84	31.41	**11.56**	**9.2%**				
		(in)consistency range	2.07	1.92	1.37	1.30	1.41	2.07	2.72	2.21	3.50	**3 tests % average**	**8.40%**	**2.06**	**1.7%**	**1.30**	**3.50**
		Control points position	-16.00	-16.00	-16.00	-12.33	-16.00	-16.00	-16.00	-12.33	16.00						
		Test 108	-24.23	-25.70	-21.70	-5.60	-20.52	-23.87	-20.23	-8.87	25.70	**6.68**	**5.3%**				
5		Test 109	-26.45	-25.99	-20.15	-5.16	-20.79	-26.93	-23.76	-9.15	26.93	**7.71**	**6.2%**				
		Test 110	-26.11	-26.52	-21.96	-5.95	-20.38	-25.52	-22.42	-9.09	26.52	**7.45**	**6.0%**				
		(in)consistency range	2.22	0.82	1.81	0.79	0.41	3.06	3.53	0.28	1.23	**3 tests % average**	**5.82%**	**1.57**	**1.3%**	**0.28**	**3.53**
		Test series totals calculated in relation to foam blank height (125 mm):											**4.66%**	**2.56**	**2.04%**	**0.28**	**6.57**

Table. 1 Data from the Key Stage 2 test series (tests 93, 94 and 95 are omitted from the table, as these were not carried out with the Perspex foam-setting frame).

- **To test the production repeatability of the system.**

As the RPT system was developed with a view to facilitate a highly flexible production, this objective could appear somewhat contradictory. However, the capacity to reliably reproduce a set shape was considered to be a good indication of the system's overall capabilities. Furthermore, the system was envisioned as having the capacity to be operated seamlessly as a prototyping tool as well as a reliable production method for creating standardised batch products.

Throughout the testing process several investigations were undertaken to establish the system's capabilities for replicating shapes. As described in the previous subsection, the method of testing the repeatability of the system was to set the RPT system to a particular shape and then produce multiple cut foam shapes from this set shape.

Several test series were undertaken with this approach, which all seem to indicate a level of variably in the foam shape output. The researcher considered the cause of this variability to originate from the inconsistencies in the way the foam compresses, as highlighted in 7.2.10.3. In some of the early tests these inconstancies might also have been caused by slight inconstancies in the alignment of the bandknife. Any slight misalignment of the bandknife blade would be greatly exacerbated due to the foam being compressed to less than half of its natural size during cutting (as previously highlighted). Equally, minor misalignments of the foam blank in between the pin units may also contribute to the inconsistencies in the output in the earlier tests. But as the Key Stage 2 test series employed the Perspex foam-setting frame, this issue could also be largely discarded as a contributing factor.

In summary, Key Stage 2 tests provided numerical data to make an assessment of inconsistencies on based empirical data collected with consistent conditions in a series of 18 tests. To isolate the issue of inconsistency from the issue of inaccuracy, the sampling points from each of the three repeated tests were assessed independently from the control point position, and the variability in the position of the sampled points were then expressed as a range between the *lowest* and the *highest* sampled position. This was expressed as the '(in)consistency range' and listed under each of the nine point sampling columns, see Table. 1.

Further analysis of the sampling points on the 18 tests are listed in the table as overall averages expressed in both millimetres and in terms of a percentage figure. The percentage inconsistency rates are calculated in relation to the 125mm height of the foam blanks. The lowest inconsistency range in all of the tests is found in sampling point eight in test shape five where there is just a 0.28mm range between the sampling points on the three test shapes. The highest inconsistency range was found in sample point three in test shape three, where the position of the sampled points were within a range of 6.57mm. The average inconsistency rate per shape ranged from 1.57mm in test shape five to 4.51mm in test shape two. The overall, average inconsistency rate of all the shapes is 2.56mm. This figure can be expressed as an inconsistency rate of 2.04%.

This level of inconstancy can be considered to be a reasonable result. Online foam suppliers quote dimensional tolerances of up to 5mm (Mark Harris Upholstery Ltd, 2015), and therefore, the consistency achieved with the RPT system is in-line with the current standards of the upholstery foam industry. However, it should still be noted that the evidence from the tests indicate that whilst an average 2-4mm variability is likely to be the norm, certain settings may produce shapes that differ dimensionally up to 5-6mm. While an even lower level of inconsistency would be desirable, it is likely that there are still elements in the system's set-up which can be improved, and through such improvements the system's capacity for repeatability is likely to increase.

- **To test the accuracy of translating digital design data into physical foam shapes**

Clearly, the results from the previous objective, concerning the system's capability in terms of producing a repeatable output, has to be taken into consideration as a contributing factor when testing the system for accuracy in translating digital design data into physical foam shapes. To assess this capacity, the same test series data is used to establish the inconsistency range.

In order to isolate the investigation of accuracy from the issue of inconsistency, an average of all of nine sampling points were calculated against the control point data. Crucially, the sampling point figures were all converted into absolute numbers (positive values) as otherwise the sampling points lying both above and below the control data point could potentially have *evened themselves out* to provide an average figure, thereby falsely indicating an overly positive assessment of the system's accuracy capabilities.

The level of inaccuracy in the table is again calculated as a percentage in relation to the height of the foam blanks of 125mm. Discounting the figures for the flat base surface, the highest level of accuracy was found in test number 99, which returns an average inaccuracy of just 1.1%. The poorest level of accuracy was found in test 107 with 9.2%. However, given the system's issues with inconsistency covered in the previous subsection, it would be somewhat misleading to draw a conclusion based on isolated tests. A far more robust assessment is provided by calculating an average percentage based on the three repeated tests. Using this calculation it can be established that shape two still provided foam shapes with the highest level of accuracy with a 2.29% level of inaccuracy. The worst performing shape in this regard was test shape four with an 8.40% level of inaccuracy. Taking the test series as a whole, the average inaccuracy level stands at 4.66%, and this figure equates to an average of 5.34mm.

Most foam shapes produced during testing had a reasonable visual likeness to the digital design data that was used to create them. However, the data from the test series indicates that certain shapes had a worse accuracy rate in relation to the design data. Test shapes four and five both returned relatively poor figures in this regard, but from this data it was difficult to identify which particular shape features were prone to inaccuracy: a larger test series may help to clarify this issue.

As previously mentioned, the compression rate might have been a contributing factor in regard to the level of inaccuracy in the system. While all the tests were carried out with the same rate of compression of 57% (or 80mm) in relation to an 125mm foam blank, the data from the final test series indicates that certain shapes may benefit from a different compression rate, which might result in better accuracy.

The use of the Perspex foam-setting frame might also have contributed to the inaccuracy levels. The researcher carried out three tests using the base surface with the Perspex frame (tests 90,91 and 92), and three tests with the same setting but without the frame. The tests carried out with the Perspex frame all had a characteristic slight curvature, while the tests undertaken without the use of the frame had very flat and straight surfaces (but were far more inconsistent in terms of the location of the cut). The differences might be due to way the foam slides against the sides of the Perspex frame as the compression is being applied affects the way that the foam compresses, which then ultimately impacts on the shaping of the foam.

The researcher expects that some issues in terms of inaccuracy could potentially be addressed by building compensational values into the Grasshopper definition. Potentially, the foam's compression performance could be simulated with the 'Kangaroo' physics module and the Grasshopper’s evolutionary solver, Galapagos, could then be employed to predict the best possible pin setting.

- **The impact of the shape topography on the system accuracy**

Throughout the testing stages there were strong indications that certain shapes would lead to variation in the level of shaping in the foam pieces. Initially, this evidence was based mainly on the visual inspections of the foam pieces produced, however, the numerical data from the Key Stage 2 tests provided a good opportunity to make a much more accurate assessment of this issue. The figures from this series delivered clear evidence for a significant impact of the shape topography on the accuracy of output of the system. When looking at the data, sampling points gathered from test shape one show that all of the figures are lower than the control points. These figures clearly indicate that all of the three tests of shape one (test 96,97 and 98) are shaped to a lesser degree than the digital shape design data.

In contrast, all of the sampled points from the three tests with shape five returned figures that are considerably higher than the control points. This clearly demonstrates that the foam shapes are formed more acutely than the digital design data input. This is evidence that, when using the same compression rate and set-up, some shapes will be shaped more subtlety than the design data, while others will be shaped much more heavily. Indeed, the variation in the level of accuracy in all of the shapes provides further evidence that the topography of the shape design data has a significant impact on the accuracy of the foam output.

While there is evidence of the shape design (topography) impacting on the system’s level of accuracy in the foam shapes produced, from the available data it is difficult to clearly identify how particular shape topographies will impact on this issue. It seems that designs with topographies on, or near, the edge of the pin matrix will be shaped to a higher degree than designs with topographies that lie deeper within the pin matrix, such as shape one.

While this could be interpreted as an inherent flaw in the concept, the researcher considers that this issue could also potentially be overcome by enhancing the current Grasshopper script to adjust the setting data for the pin units in order to compensate for this situation. This is a solution that has already been discussed in relation to the previous objective; as a remedy to adjust the compression rate.

- **To test the durability and reliability of the system**

Initially, several of the mechanical aspects of the system caused the researcher concerns in terms of the system's long-term durability. Some of these aspects were addressed through improvements and adjustments made to the system during pilot tests as well as in the Key Stage 1 tests. An example of a durability issue, which was addressed at an early stage, was the change of acrylic to aluminium as the material used for the supporting panels for the central (locking) matrix plate.

Despite such alterations, the system still included elements that the researcher considered to be fragile and vulnerable to wear and tear. The spring sections and the fixings of the pressure bolts to the central locking plate caused particular concerns. To investigate if any problems were developing in the system, one of the pin units was completely dismantled and inspected. This inspection showed no indication of wear or potential problems in terms of long-term durability. Equally, none of the Key Stage 2 tests indicated durability issues, therefore it is reasonable to conclude that the core operation of the current system has a good potential for longevity.

The aspect of reliability should be seen as a separate issue from the system’s performance in terms accuracy and repeatability, which were discussed in subsection 7.2.10.4. The term ‘reliability’, in the context of this system, predominantly refers to the performance of the locking mechanisms both in terms of the pins as well as the sledges. The pin locking mechanism appeared to perform very well with only a couple of incidents where any of the pins were observed to move out of their locked position. These incidents happened very early in the test series and can be attributed to the bolts operating the locking plate not being tightened enough. Some *tuning* of the individual locking springs (by removing the pin and pressing the particular spring to engage the pin better) also helped to eliminate the issue with pins slipping out of position.

Fig. 114 Tuning the central pin locking plate and operating the locking mechanism via bolts enabling lateral pressure to engage the pins, photos: T. Jørgensen, 2012-14.

Generally, the locking mechanism on the sledges also performed well. However, during the stage where the compression is applied to the foam (by manually applying a firm push to one of the sledges) the opposing sledge was observed to move slightly out of position on a few occasions. Placing the end of the RPT unit against a rigid edge during compression alleviated this issue. Once the system had been locked with the foam in compression no movement in the sledges was observed.

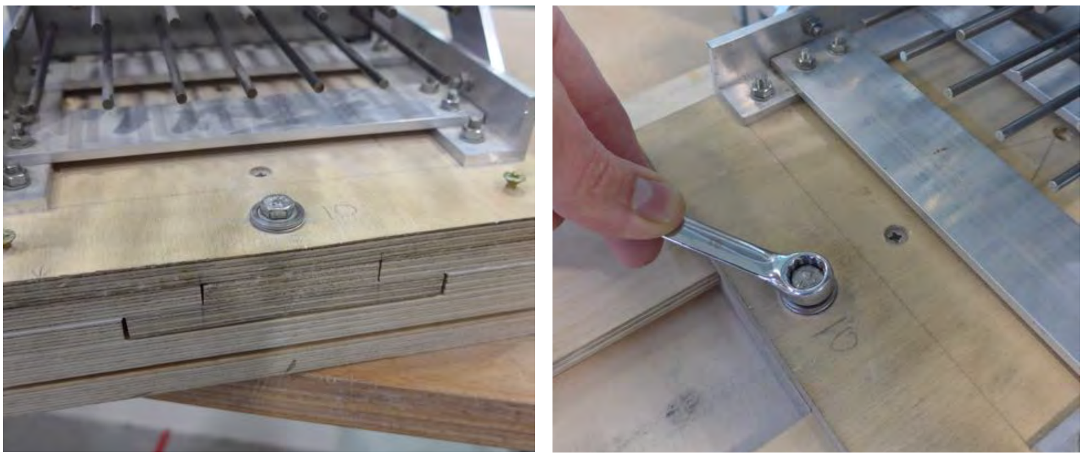


Fig. 115 Images illustrating the operations of the sledge locking mechanism, photos: T. Jørgensen, 2014.

In conclusion, the reliability, specifically in relation to the pin and sledge locking mechanisms, performed well in the later tests. However, further improvements could still be made to both of these mechanisms. Currently, the process of engaging and disengaging both of the locks requires the use of a spanner. The introduction of some kind of lever system to operate the locks is likely to improve both the speed and the ease of use significantly.

- **To test the system in the context of other furniture production aspects**

As the foam RPT system was conceived and developed in consultation with an industry partner from the furniture design sector, it would be natural to consider how the system could potentially perform in relation to typical elements of furniture production.

The production of foam elements is usually just one part of many stages in a complete furniture production sequence, and the production of upholstered furniture would most commonly involve a number of elements, materials and processes. Usually a frame or structure is needed to provide rigidity to the furniture piece and, equally, an upholstery covering is also typically employed. The researcher instigated an investigation to explore the foam RPT system in the context of such typical furniture production. The following subsection covers the various elements of the investigation including the design concept, the production of the furniture frames and the development of the fabric covering.

The researcher's vision for the foam RPT system was to integrate the system as a part of a complete production sequence involving other fabrication technologies, potentially in a coordinated production sequence facilitated by the use of the same digital design data. To explore this vision, an investigation with a focus on creating complete furniture pieces using the RPT foam moulding system as an integrated part of the production process was undertaken.

In this study, a pair of matching seats was chosen as a suitable furniture format to explore. The choice of this type of furniture also allowed a particular design response that closely corresponded to the production capacity of the foam moulding concept, which will always result in the production of two perfectly matching foam sides. While the system could potentially be employed with the intention of using just one of these opposing shapes, the other side would then constitute waste.

While upholstery foam off-cuts can be reconstructed into a recycled foam product, such foams are of a very low grade. As a consequence, foam off-cuts holds no commercial value and furniture companies therefore try to minimise any foam waste. In response to this situation (and in order to utilise both sides of the foam shapes), the researcher proposed a simple furniture concept which consisted of a pair of seats which could be stored stacked together with the matching surfaces interlocking each other.

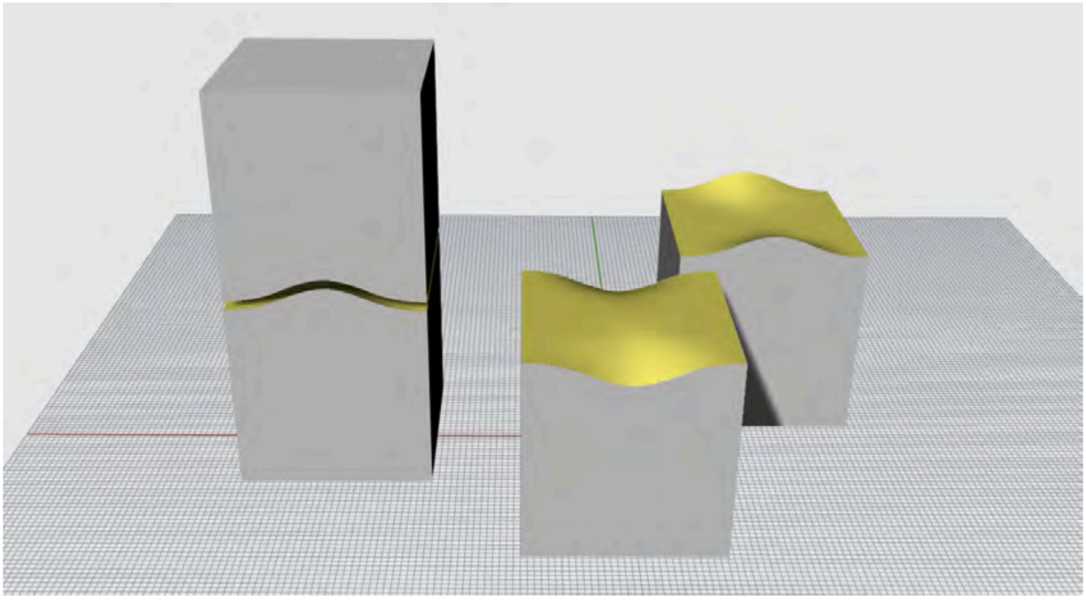


Fig. 116 Stacking seat design by T Jørgensen (2013) utilising the double sided nature of the output from the foam RPT concept.

The basic shape of the individual seats was designed as a simple box with the top shaped surface as the core aesthetic feature. The box format of the seats was designed with a cross section of 300 x 300mm to enable the top surface to be constructed from four individual tiles of foam (150 x 150mm), which corresponded to the system capacity of the foam RPT system.

Designing the seats with a top surface constructed from four individual pieces of foam also enabled the researcher to use this investigation to test the RPT system's capacity in terms accuracy in relation to the digital design input. A Grasshopper definition was created specifically for designing and producing tiled foam surfaces with a G-Code output for each of the separate foam elements (illustrated in Fig. 90). The production of each of the individual foam tiles was carried out in the same manner as all the other foam tests, although labelling the foam tiles was an essential part of the process in order to locate the tiles correctly to create a compound shape.

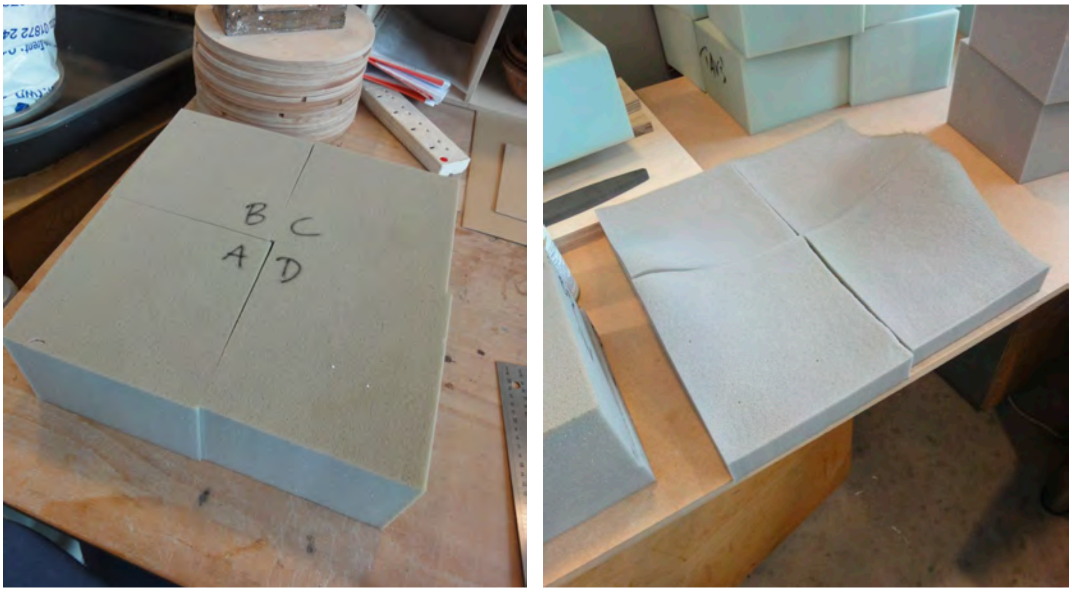


Fig. 117 The labelled foam blanks and the shape tiled together after the cutting, photos: T. Jørgensen, 2013.

Foam tiles were produced to create three different seat designs. The RPT system's performance in terms of accuracy and consistency was somewhat exposed in this process, which made the production of the seats a slightly challenging task. During the process of creating the compound shapes, the researcher had to produce a number of extra foam tiles to achieve a reasonable *flow* between the four foam shapes that made up the compound foam surface.

The process of joining the foam tiles into one compound surface was also a somewhat cumbersome and time-consuming task. Each of the four tiles had to be trimmed by 17.5mm on the adjoining sides to remove the excess foam that was needed to prevent the foam blank from sliding off the pin tips during the compression stage. After this trim, the four tiles were glued together using a spray adhesive. Following this stage, further trimming of the external sides (again by 17.5mm) were carried out before the foam shapes were finally ready to be combined with the other construction elements of the seat.

The internal frames of the seats were assembled as simple plywood boxes, which were then covered in 25mm thick foam to provide a consistent *soft feel* on all sides of the pieces — potentially also enabling the use of the pieces as seats when positioned on their sides.

Fig. 118 The construction of the plywood frames for the seats. Upholstery foam was glued to the sides to create a consistently soft feel to the seat design, photos: T. Jørgensen, 2013.

While the construction of the frames was carried out entirely with analogue fabrication methods, the production of the fabric covering for the seats was aided by use of digital fabrication technologies. The initial vision was to generate pattern cutting templates from the same data that was used to the design the foam shapes. However, based on results from previous tests it was evident that the RPT foam system's performance in terms of accuracy was not good enough to allow the same design data used in creating the foam pieces to be used directly to make the fabric covers. In response, the researcher used the RPT system's digitising facility described in subsection 7.2.8. The digitising process produced point cloud data that could be imported into Rhino 3D and used as the basis for creating surfaces from which the fabric templates could be developed.

In order for such 2D patterns to be generated, Rhino's 'advanced flattening' command was used. This command enabled the creation of fabric cutting templates for the seat's curved top surfaces. The initial intention was to automate this series of digital modelling tasks in a complete Grasshopper script, but an advanced flattening command was at this stage yet to be implemented in Grasshopper. The generation of the fabric templates could therefore only be partly automated within a Grasshopper definition with some operations carried out as *manual* modelling operations in Rhino. A specific Grasshopper definition was, however, scripted to facilitate the templates to include hemlines.

After developing the patterns the templates were then laser cut in thin ply with the view of using these in combination with a manual fabric-cutting wheel. Direct laser cutting of the upholstery fabric was also attempted but this produced unattractive burned edges in fabric. The ‘Camira Blazer’ (Camira, 2015) range was selected as the fabric for this aspect of the research. This commercial grade upholstery fabric is used extensively by MARK Product and therefore an appropriate fabric option to use with these tests.

Fig. 119 The cutting and sewing of the upholstery covers. Collaboration with embroiderer Vicky Porter, photos: T. Jørgensen, 2013.

In the process of sewing and fitting the fabric covers, the researcher collaborated with an artisan embroiderer, Vicky Porter. This was the only time during the practice enquiry where the researcher actively collaborated with another practitioner, and while some services were commissioned from commercial companies and suppliers, the researcher carried out all other aspects involved with the development and use of the system without direct assistance from others.

In order to highlight the distinctive curved designs of the top surfaces of the seats (particularly the edges) an unusual approach was developed in terms of creating the fabric covers. Instead of hiding the seam lines on the internal side of the fabric covers, these seams were located on the exterior of the seats. In order to prevent the fabric edge from fraying in this more vulnerable position, the fabric sections were cut at a 45º angle in relation to the weave direction of the cloth, which is known as the fabric’s ‘bias’. The base of the seats were also covered in the same fabric and joined with the sides of the main covers by strips of Velcro.

Fig. 120 The seats nearing completion. The fabric covered wooded base of the seat is shown on the left in the image, photo: T. Jørgensen, 2013.

While this part of the practice enquiry did result in the production of six seats the system in its current form is still not sufficiently developed to be used as a viable manufacturing system in general furniture production. The issues which most severely restrict the potential application of the foam RPT system in this context are those concerning the accuracy and consistency of the output from the system — as the results from the Key Stage 2 tests indicate. These issues are particularly exposed when the system is used to create compound foam shapes made up of several individual foam tiles.

There are also other issues with the system that need to be considered before it can be presented as a production system, notably the considerations regarding foam wastage. This would be a issue if the other half of the foam shape (which is inherently always produced by the system) cannot be directly utilised within the design of the pieces produced. A certain level of trimming of the sides of the foam shapes is probably also an inherent aspect of the concept.

In discussing the system, the core feature of developing a system that can produce a variety in the shapes output is highly relevant. Clearly, to take full advantage of this capacity any real life application of the foam RPT system should have this feature at the forefront of its use, with an RPT system unlikely to present a significant advantage in a furniture production that is focussed on the production of the same, standardised design.

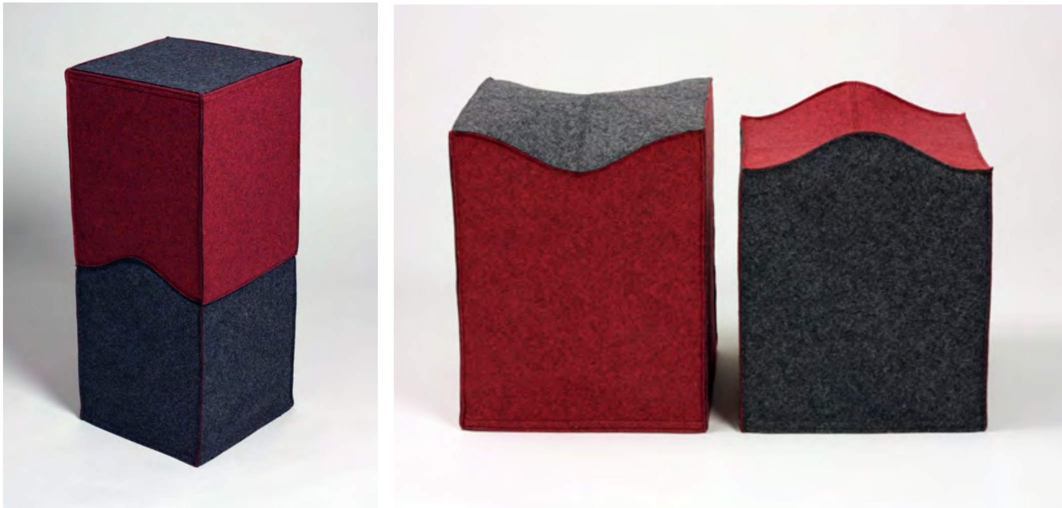


Fig. 121 Completed seat design with the stacking feature illustrated on the left, photos: T. Jørgensen, 2013.

Based on the system's current capabilities, the most appropriate application is probably in the production of bespoke or customised artefacts, but the system might also have relevance in a design and product development environment where a high degree of shape iterations would take place. However, it should be highlighted that the above text reflects the researcher's own assessment of the viability of the foam RPT concept in furniture sector. The interview with the MARK Product, which is covered in subsection 8.1, also includes a viability assessment of the system provided by the directors of MARK.

- **To assess other potential commercial contexts for the system**

While the initial intended application for the foam RPT system was within general furniture production, the concept may have much stronger commercial prospects in more specialist market sectors.

Throughout this study the medical sector has been suggested by others as presenting good commercial prospects for the concept. The researcher concurs with such views and considers the system's particular capacity for using digital data to produce one-off shapes could have particular relevance in creating bespoke foam products that could provide support for individual medical conditions. Such products are currently provided by companies such Starcushion (Star Cushion Products, Inc., 2015). However, for the RPT concept to present a viable prospect in this field work still has to done to improve the system's accuracy of translating digital design into the physical foam. Improved repeatability would also be desirable, but is perhaps a less critical aspect in such an application.

Other potential market sectors for the concept may also include high performance sports equipment that requires foam shapes to be customised to achieve optimum performance or fit. A company from this sector has already approached the researcher to express an interest in the system.

To avoid the problems involved in the production of compound shapes constructed from individual tiles of foam (as highlighted in the previous subsection), RPT systems developed for medical or sports performance applications should be of a scale where such tiling would not be needed. For example, for a wheelchair cushion the RPT system capacity should be able to produce a complete seat in a single operation.

7.2.11 Overall Assessment of the Foam RPT System

The results from the tests of the foam RPT system provide a slightly mixed picture. As a basic principle the foam RPT concept does appears to work well, however, the system's performance in terms of accuracy and repeatability do remain as issues where improvements could be made. However, it is worth reiterating that deviations in this regard (averaging 2-4mm) are still well within the industry standards for upholstery foam cutting in general.

The part of the investigation that explored the integration of the foam RPT system in a complete furniture production sequence resulted in the production of six seats. This investigation showed that the concept has the potential to be successfully applied in a practical design and fabrication scenario, particularly when the inherent nature of the RPT concept is integrated in the design response.

In relation to aspects such as durability and reliability, the system was found to perform very well indeed.

It is also highly relevant to highlight that while these tests were entirely focussed on the foam RPT application, several *generic* issues with the RPT concept appears to have been resolved in this system. Specifically, the system features a very effective locking mechanism with a fast setting time, both issues that other researchers have highlighted as still largely unresolved (Munro and Walczyk, 2007). Furthermore, the system is also likely to be easily scalable to accommodate an increased capacity, all at a very reasonable construction cost. The contextual review indicates the combination of these features has so far been a challenge for other researchers and innovators to resolve.

From the results of this investigation into a foam RPT system, it is the researcher's assertion that, as a generic RPT approach, the system that has been developed, has a good potential for specialist application of shaping upholstery foam, and also presents significant potential as the basis for many other applications with the RPT principle. Manipulation of various types of sheet mediums would be an obvious target, potentially, with entirely new types of materials.

8 Industry Interaction

From the outset, this study was intended to be informed by industry interaction both from a local perspective and also more widely. In the preceding chapter industry interaction has already been described and discussed on numerous occasions, particularly in relation to the development of the foam RPT system. This chapter is intended to provide an overall summary of this aspect of the study, and also provides the results and analysis of a semi-structured interview carried out with the study's main industry partner, MARK Product.

Industry interaction was undertaken on two different levels during this study. One level was carried out as scoping and fieldwork activities, which were on-going aspects of this study. Industry engagement in this regard mainly concerned visits to factories and workshops but also included meetings with key practitioners from industry and commercial contexts. These activities were focused on the furniture and digital fabrication industries, although it should be noted that the term 'industries' refers to a wider sector description that includes individual practitioners (sole traders) as well as larger enterprises.

The other level of industry interaction was the on-going relationship with the local industry partner, MARK Product. During the study several meetings were held with the directors of MARK to identify potential applications for the RPT system in the furniture sector. Later in the study such meetings were predominately focused on guiding the development of the prototype foam RPT system to ensure a level of industry relevance for the production system. The impact from this engagement has been referenced throughout subsection 7.2 which covers the foam RPT system strand of practice-based research.

The researcher considers that engagement with industry through the scoping activities and the relationship with MARK Product were both instrumental in framing and developing the practice enquiry as well as developing more conceptual considerations in this study. It is relevant to highlight that the initial intention was to create a system that could reach a level of development where a *live,* case study trial could have been undertaken with MARK Product (or one of the company's sub-contractors). However, while the development of the foam RPT system was a direct result of consultation with MARK Product, the duration of the study did not allow for the development of the system to a level where such a case study was feasible to undertake. As an alternative, a semi-structured interview with the directors' of Mark Product was carried out in order to record their views and responses to the development of the foam RPT system, the results from the testing stage and the complete prototype furniture pieces.

8.1 Interview with Industry Partner, Setup and Method

The methodological consideration in relation to this interview has already been outlined in the methodology subsection 6.5.3, and details for the rationale for selecting a semi-structured interview format can also be found there.

The semi-structured interview was undertaken in MARK Product Offices in Rosemanowes Quarry, Penryn, Cornwall on the 10/01/2014. Both of the company's partners, Anna Hart and John Millar, attended the interview, which lasted about 50 minutes.

Prior to the meeting the researcher had prepared a list of topics in order to structure the interview to ensure that issues of particular importance were covered in the discussion. These issues were summarised in the following themes:

- **Recap of the project and progress report from the researcher**
- **The MARK Product business sector and nature of operation**
- **Notions of bespoke / customised production**
- **Local manufacturers and provenance**
- **The potential application of the foam RPT process in MARK Product's business**
- **Tools for innovation/production and the wider notion of tooling**

The subsection below will present the data from the interview with selected quotes relating to the issues discussed. These issues have, in turn, then been organised into the key themes. A discussion then follows including a presentation of the researcher's interpretation and analysis of the data. Coding was not formally employed in the analysis of the interview data as the key issues were deemed to have been relatively well-defined from the outset.

Fig. 122 Still image from the video recording of the interview with MARK Product partners, John Miller and Anna Hart, photo: T. Jørgensen, 2014.

8.1.1 Results of Interview in Response to the Key Themes

This section provides the data collected from the interview with responses organised in relation to the key themes identified by the researcher. Each theme will be introduced as a bullet point, with a short description and rationale for the theme.
This structure does not represent the interview chronologically, but is a thematic collection of responses and discussions from various parts of the meeting.

- **Recap of the project and progress report from the researcher**

As an introduction to the interview the researcher outlined the aim and structure of the interview. This was done through a pre-prepared PowerPoint explanation (via a the researcher's laptop screen). During this presentation the researcher provided a recap of the title of the study, a brief summary of the research question and the overall aim of the research. This presentation included a brief outline of the history of RPT, other contextual elements of the study and some of the key concepts that were being addressed through the research. The researcher also briefly outlined the current level of progress with the foam RPT system and reported on some of the latest test results. This presentation was supported by physical examples, which the researcher had brought to the meeting. Miller and Hart were already fairly familiar with this material, but the recap insured that a general understanding of the underlying issues, context and the current state of system's development was shared among the involved parties.

- **The MARK Product business sector and nature of operation**

This theme was included to get Miller and Hart to summarise their company's business activities, and to explore which elements of their business provided the company with a competitive advantage. While the researcher had significant prior knowledge of MARK's operation, this line of discussion was included to give Hart and Miller an opportunity to provide an up-to-date assessment and also to open up discussions relating to a wider business sector context with a view to relating the foam RPT system to these positions.

Initially, Hart summarised the MARK Product's operation as: 'We are furniture manufacturers — in summary, but in a variety of materials', and reiterated this statement later in the interview by saying: 'we are UK manufacturers'. This statement was notable as it was evident from the researcher's prior knowledge that the company does not undertake the actual manufacturing in-house, but instead commissions local manufacturing companies to undertake the production. However, later in the interview Hart nuanced this statement by commenting, 'we are not [the] makers, we are the designers'.

Hart and Miller both jointly summarised the key competitive advantage of the business as 'design', with Miller describing the company as 'design-led'. Hart expanded on this statement by commenting on the challenges of remaining competitive whilst operating with the high production costs associated with having a UK manufacturing base, stating: 'we have to be clever with the design because we don't have big factories with very involved processes, instead we are using traditional skills, but in a modern way'.

Further commenting on the issues regarding key competitive advantage, Miller indicated that innovation was also a key aspect to the company, by stating: 'we survive because of our ability to design and innovate'.

- **Notions of bespoke / customised production**

Throughout this thesis the key feature of the RPT principle has been highlighted as the concept's potential to provide the basis for a highly flexible manufacturing system capable of producing an infinite variation of forms. The relevance for such flexibility could potentially relate to a production of bespoke or customised artefacts, and this theme was aimed to spark discussions around these issues within MARK Product's operation.

At the outset of these discussions Miller stated that the majority of the MARK business relied on the ability to customise their products. However, Hart was eager to clarify this statement by noting that most of the customisation 'was done within the confines of an existing frame and therefore not necessarily [needing] to reconfigure a whole load of tooling, which would be much more expensive'.

Miller went on to explain that the company's typical customers are commercial specifiers and described these as being 'quite demanding customers' who frequently would request alterations to existing stock products — mostly in terms of the sizes.

Miller and Hart both commented that, in the process of designing a new product, they would take some account of the possibility that they might receive future requests from customers to resize a piece, and this consideration for the possibility of having to do future alterations would influence the construction of a design; although Hart highlighted that this would not necessarily be a priority issue in the design process by stating: 'we are aware of it [as a possibility]'.

The researcher also raised questions regarding the possibility of creating systems that could enable the company's customers (typically specifiers) to actively interact in the design process. Hart responded to such a suggestion strongly by saying, 'that would make me cringe' and explained further, 'people haven't got time to do that' (still with reference to commercial specifiers).

- **Environment for business and innovation in terms of subcontractors, local manufacturers and provenance**

The contextual review identified concepts of post-industrial manufacturing as being of central importance to the study. As highlighted, these are notions which have also been described as 'flexible specialisation' by Kumar (1995), with particular reference to the structures and capacity of small independent companies to co-operate on a level where they jointly provide a very efficient, but also innovative and flexible production.

At the outset of this study, it was proposed that the context of exploring and developing RPT systems should be seen within the researcher’s overall vision for a new environment for flexible specialisation founded on the emergence of digital fabrication tools. On the basis of this hypothesis the researcher deemed it to be highly valuable to explore MARK Product’s relationship with its subcontractors and the potential impact this relationship has had on the company’s ability to operate and innovate.

On the issue of provenance, both Miller and Hart described this as a 'very important' aspect of their business. Hart expanded this further by stating: 'it is important in the selling of our products', and while indicating a growing interest in this issue, Hart noted the high cost of furniture pieces made retail customers less interested in the notion of provenance, while corporate clients were better able to make considerations in this regard.

The company’s interaction with local manufacturing was discussed several times, with Miller highlighting the company’s general interest in local manufacturing and the ways that the company’s products are being made, by stating: 'the provenance thing is what makes us want to do the business — we want to do something that is here'.

The company’s relationship with subcontractors was also discussed at some length in relation to product development and prototyping. With both Miller and Hart highlighting the importance of this relationship and the high levels of goodwill they had enjoyed from subcontractors, particularly in the start up phase of the company. Miller also noted considerations that the company took in relation to subcontractors and for that reason the company could not carry out 'a new design every week' as it would potentially overburden its suppliers.

Both Hart and Miller explained that although they would generally expect to be charged by their subcontractors for carrying out prototyping work, suppliers would frequently only charge this work in relation to multiple production rates, which would not reflect the added time cost that producing non-standard pieces would incur.

Another beneficial aspect of using local manufacturers was highlighted as the ease and speed of personal face-to-face interaction, with Hart stating that the 'development [of our products] are being made so much easier by having people down the road to whom we can say — can you make this?'.

- **The potential application of the foam RPT process in MARK Product's business**

Clearly, this was a key theme to investigate during the interview. While the foam RPT system had been developed as a result of industry interaction in general, and the relationship with MARK Product in particular, the system had still been developed by the researcher *without* direct instruction from MARK Product. Nor had the system been developed in response to an actual application need or requirement within the MARK Product's business. With the state of the system's capability reaching a reasonable level of maturity, the interview provided a good opportunity to get Miller and Hart to assess the system's real-life potential within their business.

Without specifically referring to the system's capabilities but commenting on the study and development of the RPT concept in general, Miller stated: 'it's relevant what you are doing because we survive on our ability to design and innovate'.

Being asked to comment on the foam RPT system specifically, Hart remarked: 'I think there are elements of what you have shown us that spark an idea — that we can use that application in certain ways'. Hart went on to reiterate the possibility of using the foam shapes to produce some sort of decorative acoustic panelling, an idea that had been aired as a possibility in a previous meeting. Hart also stated that the use of the systems would fit with the company's aim of 'wanting to do things that are innovative and new'.

Miller commented, 'I think we can [see a potential application] — but we are not sure what it is'. But Miller also commented that he was not sure how the ability to create a variety of shapes would be applied in a business context, particularly communicating this option to customers. In relation to the option for clients to specify a complete new shape or design, Miller commented: 'not many people would engage with that [process]', instead Hart highlighted that clients prefer to choose to customise pieces from an existing range, and expressed that the requirement for a piece to fit to a certain spatial situation would be the most common reason for customisation.

Hart also expressed an interest in the potential of being able to generate both fabric patterns and foam shapes as an output from the same design system (with reference to the use of parametric scripting). While acknowledging the frequent use of three-dimensional shaped foam shapes in the furniture industry, Hart also highlighted potential problems in terms of using the system for functional pieces of furniture by expressing concerns in the way that the foam shapes might wear over time due to the lack of tension being applied by a fabric (these comments were specifically directed towards the prototype seats that had been developed by the researcher).

Discussion in relation to the potential use of individual elements of the system was also undertaken. The development and use of parametric modelling scripts was highlighted on several occasions as being of particular interest to the company. Miller commented on this issue by stating: 'I think we can do a lot with that', and highlighted the *Wave Table* design (MARK Product, n.d.) as a relevant product where such scripting could be implemented.

In an effort to interrogate the central claim in this study concerning the potential for the idea of flexible tooling, both Hart and Miller agreed that it definitely could have relevance in a company like MARK Product. However, Miller nuanced this position by stating that as the company works with a wide range of materials and processes, a commitment to a particular process may result in a manufacturing focus on a particular process or material, which, to a degree, went against the aim of the company to design with a diverse range mediums and manufacturing processes.

- **Tools for innovation/production and the wider notion of tooling**

This theme concerns the underlying hypothesis of the study that access to development tools is one of the key foundations of innovation, particularly in relation to individual practitioners and small businesses. This theme was also intended to explore other remarks and reflections on the wider notion of tooling.

This theme also included a specific line of questioning which referred to the foam RPT System, specifically aiming to explore whether the system should be seen as a design, prototyping tool or as a flexible, manufacturing tool. Hart expressed that she clearly saw the system as a manufacturing tool rather than prototyping tool, by stating: 'this is a manufacturing process', and outlined the typical design process used by the company as starting with sketching, which then would progress to the creation of physical models or prototypes. Hart expressed scepticism for the use of the system for prototyping, particularly if the actual production would not be carried out on the same system.

Both Miller and Hart seem to be in agreement that a potential foam RPT tool would be more suitably located in the premises of one of their suppliers, rather than being placed in the company's own design office (or prototyping workshop). The researcher suggested that this position perhaps was as a result of being able to work with suppliers in close proximity, to which Hart agreed.

The researcher initiated a line of discussion that investigated Miller and Hart's views on the potential benefit of having a flexible tooling system in general; one that would allow for continued iterations and improvements to a design after the product had been launched. In response to this line of questioning Miller and Hart discussed the stages of tooling that had been employed in the production of the *Net Chair* (MARK Product, n.d.), describing how three different tools (all welding jigs) had to be produced.

Initially a very basic tool was made to manufacture the very first pieces for the product launch. Another tool was then constructed to produce the following 100 pieces and finally a very expensive CNC milled aluminium jig was created to facilitate the on-going multiple production. With each of the tooling stages, tweaks and adjustments were carried out.

In relation to the potential of having a tool which could facilitate such iterations to be carried out without having to create several new tools, Miller remarked 'that would be great', and also provided the example of the *Shaper Table* design by saying: 'we probably made 2-3 moulds before we got the perfect one'. However, in response to this notion, Hart also remarked that such a possibility would depend on the suitability of the material (and by implication, the associated production/tooling process).

Miller also commented that the multiple tooling stages highlighted with the *Net Chair* example was perhaps a particular issue in small companies. In contrast, larger companies with a greater investment capacity would, from the outset, be much more ready to commit relatively large funds towards the tooling costs for a new product. The large US furniture company, Herman Miller (Herman Miller, Inc., 2015), was provided as an example, with Miller commenting that there would be less need for such companies to have flexible tooling.

One of the discussions concerned the tools employed by the company in their design and product development. The researcher enquired as to the impact that CAD tools have had on their design process. Hart expressed that while such tools are useful, the use of Rhino could lead to designs which potentially could not be made. A statement that could be seen to highlight the rationale for the large amount of *analogue* model-making and prototyping, which is carried out within the company — by Miller in particular.

Although hand skills were highlighted as core in this procedure both Hart and Miller also mentioned the use of laser cutting and CNC milling being employed in their prototyping processes. The use of traditional hand skills and manufacturing processes in new product innovation scenarios were also eluded to in several sections of the interview, with Hart stating at the start of the interview: 'we are using traditional skills, but in a modern way'.

A line of discussion was explored in regard to recouping the expense of prototyping and development in the cost of the pieces. In response, Miller outlined that cost returns depended on the nature of the piece. Miller provided the example of sofa designs, where the company would expect profits after just a few items In contrast, the profit returns on a chair design might not be expected until the sale of hundreds of pieces. Hart explained that this issue was often due to having to invest in material stock for particular pieces. Miller expanded on this point by saying 'that comes back to the issue of tooling'.

8.1.2 Discussion of Interview Data

The interview confirms several of the assumptions held by the researcher. In particular, that flexible tooling concepts in this industry sector do have relevance, although a clearly defined application for the foam RPT system has not yet been identified.

Mark Product’s close relationship with its local subcontractors was also confirmed. A particular indication of the closeness of this relationship that is relevant to highlight is Hart’s initial response to questions concerning the company’s core business as being a 'furniture manufacturer', despite the company not carrying out any actual production. This answer is perhaps a good illustration of MARK Product’s closeness to its subcontractors. The actual manufacturers are perhaps viewed almost as sub-divisions of a larger collective enterprise. This is a business structure that has clear reference to the concept of flexible specialisation. It seems clearly evident that the network of specialist companies, of which MARK Product is a part, provides a particularly healthy innovation environment.

The notion of this network may also help to explain why both Hart and Miller considered the RPT device as a manufacturing device (to be used by one of the company’s subcontractors) rather than as a prototyping tool in MARK Product’s offices. MARK Product’s specialist skills are in design and the company’s flexibility would potentially be compromised if it aligned itself with a particular material and manufacturing technology. The strength of flexible specialisation comes from individual companies focusing on their specialism while remaining flexible to interact with other specialist companies on particular products.

The interview does not provide firm evidence that the access to new development tools is one of the key facilitators for innovation in MARK Product’s business. However, there are still indications from the interview data that the access to new fabrication tools, such as laser cutting and CNC routing, are contributing and facilitating factors in the innovation scenario. Although some scepticism was expressed by Hart, it seemed evident that digital design and fabrication tools were aiding the company’s product development as well as the actual production of the pieces. It also seems evident that traditional, analogue manufacturing processes are frequently combined with these digital manufacturing processes in many of MARK Product’s designs.

In summary the reaction of the directors of MARK Product to the RPT foam system is that the premise of the concept is relevant to MARK's business situation and while a specific design application is not yet identified, the overall reaction is positive, which as reflected in the following quotes, ‘I think there are elements of what you have shown us that spark an idea - that we can use that application in certain ways’ (Anna Hart). 'It’s relevant what you doing ‘because we survive on our ability to design and innovate' (John Miller).

9 Critical Discussion and Reflections

This chapter gathers the results from the practice investigations and, through discussions, relates this to the aims and objectives of the study.

The central core of this study concerns the tools and development approaches that enable the independent practitioner to innovate in the context of digital fabrication. The chapter starts with a recap of the research question and the central aim of the study. A discussion then follows of the various factors that, in particular, have been explored though the practice enquiries and identified as being significant to this innovation scenario. Other subsections reflect on conceptual insights that have developed as a result of the study. These insights concern wider theoretical positioning of the research and includes reflections on notions of 'The Role of the Moulding Medium' (subsection 9.1.3), 'Tool Use and Tool-making' (subsection 9.1.2), 'Discussions in Relation to S-curve Theory' (subsection 9.1.4), a notion of combining innovation enabling factors into an tool-set (subsection 9.1.5) and how this tool-set may enable a situation of 'Shifting Innovations Spheres' (subsection 9.1.6).

The last section of this chapter provides an analysis of the results of the study in relation to the stated aim and objectives.

9.1 Discussion

In order to validate the research and provide a relevant evaluation structure it is useful to return to the research question of this study.

- How can digital fabrication tools and knowledge resources facilitate independent innovation, focussed through an exploration of new applications for Reconfigurable Pin Tooling?

This research question implies an exploration of innovation through practice-based research. So that an analysis of this innovation process can be initiated, it is useful to establish if this practice activity has delivered innovation. Whilst the study's two practice enquiry strands concerning the development and exploration of RPT systems for moulding upholstery foam and glass are both covered in detail in chapter 7, it is evident from the description concerning the glass RPT system (subsection 7.1) that the development is of an innovative tooling system. A detailed discussion of this practice strand is provided in subsection 7.1.7, including an analysis of the particular objectives identified for this aspect of practice. This discussion, alongside a summary of this study's contribution to knowledge (chapter 11), provides evidence for the development of a number of innovative technical solutions as well as the creation of two bodies of artistic work by the researcher. Pieces from this artistic exploration have been exhibited widely and the innovative nature of this work is provided as peer recognition detailed in subsections 7.1.7 and 11.1. Through the commercialisation of these pieces a complete innovation scenario (Smith, 2005, p.107) can justifiably be claimed for this practice aspect of the study.

The description of the practice enquiry concerning the development of an RPT system for shaping upholstery foam (subsection 7.2) should also provide clear evidence for innovation. The foam shaping application is arguably novel, with a number of technical solutions also being claimed as contributions to original knowledge (detailed in subsection 11.2). However, as this practice strand did not result in a commercialisation stage, only the 'research and development' stages of the innovation scenario (see Fig. 96) have so far been explored by this aspect of the research. The analysis of the rigorous testing of the system (Key Stage 2 tests are described in subsection 7.2.10.4, with results discussed in subsection 7.2.11) indicates that there is significant potential for this practice strand to result in innovation throughout the process (including commercialisation). This assumption is supported by the data from the interview with local industry partner, MARK Product (see subsection 8.1.2), who assisted the researcher in the development of the foam RPT system by providing guidance from an industry sector perspective.

Recognising that innovation has been delivered to some extent within both of the practice elements provides a useful fixture point in the evaluation process of the overall study. Now, effectively, attention can then turn to the more central focus concerning the key word in the research question of '*how*'. This interrogative adverb is of central relevance in this study, as it was *how* the methods, tools and approaches were applied in the development stages of innovation scenarios that were of central interest to the researcher from the outset of this study. The following subsections will summarise the factors, which through the practice investigations have been identified as key to facilitating the aspects of innovation that have been established in this study.

9.1.1 Key Facilitating Factors in the Innovation Scenarios of the Practice Enquiries

At the start of the investigation the focus was on exploring tools and knowledge resources, with the researcher presuming these to be the key facilitating factors in the early stages of the innovation scenario. However, as the study progressed and data from the practice activities were gathered, the researcher concluded that the results provided a more nuanced picture. Evidence showed that other factors impacted on the process and helped to facilitate innovation in this specific field and context. In response to the findings, the results are summarized into the following factors:

- **Access to tools**
- **Access to knowledge resources and peer support**
- **Access to suppliers and the local environment for innovation**
- **Prototyping approaches**

The following will address these factors in detail.

- **Access to tools**

This factor, as a significant enabling aspect, was explored throughout the two practice strands with the researcher finding the access to cheap and powerful digital design tools as a clear enabling factor in the innovation process. A particularly important aspect in this respect is that digital design tools can facilitate a fast prototyping sequence. An example of this was the use of low cost personal inkjet printers, small laser cutters or 3D printers in the initial stages of the innovation process. The portability of the design data means that design files from initial explorative prototyping stages (using the above equipment) can be very easily submitted to external companies for fabrication using much higher-grade digital equipment. This means that bespoke parts for realising working prototypes can be fabricated in durable materials with a very high level of engineering tolerances.

Another key aspect of this factor is the relative ease-of-use many of these development tools present. For example, without the visual scripting interface of the Grasshopper program the foam RPT system would probably not have been able to be established without significant assistance from others. The researcher believes that increased ease-of-use means that the independent innovator can engage in aspects of developmental work which they had been previously unable to. While the particular combination of digital design and development programs (Rhino 3D, Grasshopper and MACH 3) used has been specific to this study, many other alternative powerful and affordable digital design software exsits. Cheap (or free) design programs have been emerging steadily over recent years (as outlined in subsection 5.2.1 of the contextual review).

In conclusion, the study has confirmed the assumption that access to affordable, powerful and easy-to-use digital design tools are a highly significant facilitating factor for independent practitioners to innovate.

- **Access to knowledge resources and peer support**

The study provides more nuanced evidence for the impact of this factor in the innovation scenario. Based on both general media attention and also academic literature (Gershenfeld, 2005; Raymond, 1999; Von Hippel, 2005) the researcher expected to find that a key factor in the growth of independent innovation in the field of digital fabrication could be attributed to peer group support, particularly via online communities. However, in practice investigations of this study the researcher did not find a particular need to interact with online communities or forums. Although it should be noted that some online knowledge resources (accessed without direct peer interaction) did provide some useful knowledge, in particular tutorials to build up skills in Grasshopper scripting.

In contrast, the interaction in physical, face-to-face situations with peers was found to be of significant of value, with the CNC Homebrew workshop providing a particularly important impact. It is relevant to highlight that this observation could just be specific to this project and other projects concerning different technologies might find online support resources to be of significant value. Even so, it was found that peer group support was only needed at a few key stages of the practice enquiries. For the vast majority of the time spent during the practice investigations, the researcher worked almost completely independently, and recognises that, for him, online descriptions and postings of other projects concerning digital fabrication mostly served as an inspirational role rather than as actual sources of technical information.

- **Access to suppliers and the local environment for innovation**

At the outset of the study the value in a good supplier network was recognised and it was proposed that the notion of 'flexible specialisation' could serve as an inspiration to rekindle local and regional manufacturing through the use of digital fabrication tools. However, it was only through the practice enquiries it was realised how critical the access to a network of suppliers is to this particular innovation scenario. This factor contains some of the more surprising findings of the research.

Further evidence to support this conclusion is provided through the interview with the industry partner of this study, MARK Product. In this interview both John Miller and Anna Hart repeatedly highlight the importance of the company being in close proximity to suppliers and sub-contractors. This was emphasized not just in terms of the production of the company's actual pieces, but, perhaps more crucially, in terms of the development of new designs.

While the importance of the local environment has been repeatedly highlighted throughout this thesis, the researcher believes that the notion of flexible specialisation, as described by Kumar (1995) and also Lazonick in Fagerberg et al., (2006, pp.35–37), as seen in the current context have some different characteristics from the historical examples previously presented. In addition to the facility to collaborate or source services from a local network of specialist companies, the individual innovator can now also use the internet to create an additional network of flexible and specialist subcontractors and service suppliers. A more current model for flexible specialisation could therefore be presented with two spheres of network; a local one based on interaction with companies with a physical presence (bricks and mortar) and a remote one, consisting of companies where only web interaction is undertaken.

In relation to this study, an example of this structure can be presented as the local suppliers of stainless steel components and aluminium profiles as representing the local sphere of flexible specialisation and with the remote sphere consisting of those companies which supplied the specialist CNC parts, such as control units, stepper motors, and linear bearings/rails. Based on the results from the practice enquiries, the researcher argues that the prospect of building a flexible network of specialised suppliers to support innovation as a combination of these two spheres presents great opportunities for independent innovation in the field of digital fabrication.

The researcher found that the two spheres (local and online) of suppliers could be separated further into subcategories: suppliers of the specific technical parts for the development of digital fabrication systems, and suppliers for the materials that the fabrication systems manipulate. The building of a CNC system still remains a fairly specialised activity and, consequently, very few of the parts can be sourced locally. Most CNC parts are generally only available via online suppliers, which, in contrast, are plentiful and enable the sourcing of parts to support almost any level of technical engagement with CNC technology. The foam RPT investigation confirms this environment of suppliers as the researcher found that affordable parts for building CNC machines were widely available from online sources. This was a very important facilitating factor in this particular innovation scenario.

Other, more general construction parts (such as nuts, bolts and metal profiles) were found through local suppliers with physical shops and were found to be a more preferable sourcing option. The ability to view and handle potential parts was found to be of particular value. The other subcategory of suppliers concerns the stockholders of the physical materials that the fabrication systems are intended to manipulate. In both of the practice enquiries local suppliers were found to be a very significant enabling factor in the innovation scenario. In this category of suppliers, the position was almost reversed from that concerning the suppliers of specialist CNC parts. In this category certain materials were found to be, in practical terms, only possible to source from local suppliers (the supply of sheet glass provides a good example of such a situation). Equally, the researcher found that the personal interaction with suppliers provided access to highly valuable knowledge about the characteristics of the material and included industry insights. Such knowledge would have been very difficult been to retrieve from online sources.

In conclusion, it seems evident from this study that a network of online as well as local suppliers provides an environment to enable the independent innovator to operate increasingly effectively. These two types of suppliers can be seen as providing the independent innovator with a support network that can be seen as new — a hybrid type of flexible specialisation.

- **Prototyping approaches**

In the practice elements of this study the researcher has tried to adopt the developmental approaches that are characteristic of some of the key subcultures that are currently associated with independent innovation activities, notably the Maker Movement and hacker communities. Such approaches are typified by development through practical prototyping rather than theoretical pre-planning. Innovation approaches from such subcultures are also based on the frequent appropriation of found elements and parts salvaged from existing technologies into the construction of new systems.

The researcher found, in his explorations, that such approaches had distinctive advantages, particularly in terms of the speed of the prototype iteration. It can also be argued that these methods can be identified as having led to the development of specific technical solutions within the RPT systems; a solution which most likely would not have been achieved had other developmental approaches (such as those based on theoretical planning) been used.

Through the practice enquiry the researcher undertook further explorations of the specific elements within this factor. The researcher identified, in these explorations, a number of specific aspects and approaches that are useful to adopt at certain stages of a development methodology that is based on practical prototyping. These aspects, which include ‘speed', ‘flexibility’ and ‘accuracy’ are discussed in detail in subsection 7.2.9.

9.1.2 Tool Use and Tool-Making

The notion of tool-making remained a core theme throughout this study. During the practice enquiries the researcher developed (and used) a number of new tools — both physical and virtual. In both of the practice strands the overall goal was to create complete tooling systems, but in order to establish these systems the researcher frequently had to create supporting tools and jigs within the process of developing the final systems. Throughout this study the researcher has reflected on the idea of the tool-making sequence and developed an increased interest in this notion.

While attending a think tank at the Chipstone foundation, the researcher presented his early ideas on this subject by describing the sequences of tools needed in the process of creating other tools as a 'chain of tools'. By this, it is meant the sequence of supporting tools and jigs, which have been created solely for the purpose of creating other tools. The contextual review briefly discusses the impact of tool-making capabilities on certain historical waves of innovation (such as the first industrial revolution). In relation to this, it would be an interesting exercise to identify all the *supporting* tools that were used in the undertaking of the two practice strands of this study. However, this is likely to be a very onerous task and within the capacity of this study it not would be possible to establish a complete and comprehensive list of such supporting tool-use and tool-creation. Nonetheless, it is still relevant to highlight examples of some of the distinctive tool and jig making scenarios in the study.

Fig. 123 Examples of tool and jig making. The two images on the left illustrating a tool created for clamping pins while grinding them into consistent lengths, the central images depicts a jig for clamping matrix plates during the CNC assisted hole drilling, and on the right are two images showing a small tool set created to bend the springs in the foam RPT system into an accurate position, photos: T. Jørgensen, 2011-12.

One example of the creation of a tool that performed a purely supporting role in the development process was a jig to enable the researcher to accurately grind the pins to an equal length (highlighted in 7.2.3). In the glass RPT practice strand Perspex jigs were also created to hold the matrix plates of the glass RPT system in position during the process of drilling the holes for pins via CNC. Another example of *supporting* tool-making included a small set of tools to bend the springs in the middle locking plate of the foam RPT system into a consistent angle. This little tool set, which was critical to achieve accurate positioning of the springs, was designed in CAD and created via FDM. Overall, the researcher considers the creation of such supporting tools as being a very critical aspect in the overall innovation sequence of the practice elements of this study.

The notion of tool and jig-making was not only explored in the physical realm, but extended into the digital design aspect of the innovation process. The researcher's main tool-making environment in this regard was the Rhino 3D modelling program, which was used extensively throughout the study not only as a *direct* tool, but also as a platform to create other virtual tools and jigs. McCullough (1998) argues that a computer program should not be considered as just one tool but a collection of many (a tool-set), and this is also a very accurate description of Rhino's extensive capabilities. Frequently within a modelling sequence, Rhino's inbuilt tool-set was used to create a variety of shapes that would act as virtual jigs or cutting tools in combination with tools as subtractive Boolean operations. Therefore, the creation of designs within the Rhino program would frequently also be the result of a sequence of virtual tools created by the operator entirely within the software, and as such this process could be seen as a 'tool-making tool' developed solely as part of the process of establishing a complete design.

Equally, the creation of Grasshopper definitions are also aspects of tool-making. In particular, the definitions that were used to create the files for the designs of the matrix plates of the RPT systems are illustrations of the process of tool-making based on parametric software scripting; in effect the creation of virtual reconfigurable tools for the creation of physical reconfigurable tools.

9.1.3 The Role of the Moulding Medium

The previous subsection provided reflections on tools and tool-creation, thereby reiterating the central importance of the wider notion of *tools* in this study. The importance of this focus perhaps slightly masks another key element when it comes to tool innovation intended for the manufacture of physical artefacts. This key element concerns the material that the tool is intended to manipulate.

Several other parts of this thesis include sections that highlight the significant role that the moulding medium has played in the practical elements of this study. In both of the practice enquiry strands the material characteristics of the moulding medium (glass and upholstery foam) have had fundamental roles in the development and use of both of the production systems. While it could be justifiably argued that the material characteristics of the medium are relevant in all tooling and moulding processes, the required material characteristics in the practice elements of this study are specific rather than general.

With the glass RPT investigation, only the precise properties of molten sheet glass (heated to a particular temperature) would work with this tooling system. Equally, the foam RPT system is entirely dependent on the specific material characteristic of furniture foam being both elastic and compressible. In order to fully explore both tooling applications, the researcher had to gain extensive experience with moulding mediums and make adaptions to the RPT systems in response to the developing knowledge of the material characteristics of these mediums.

The researcher readily concedes that his initial interests and motivation in undertaking this study were rooted in the notion of tools. The RPT concept was selected as the technical focus in this study as it is an under-researched and underutilised tooling concept with a significant potential as the basis for innovation. This was articulated in the initial stated aim for this study.

In this aim there was no recognised need or desire to find ways to mould either glass or foam as primary objectives. While the researcher had to develop a number of innovative technical solutions in both of the practice strands to overcome the challenges of establishing operational RPT tooling systems, the main issues in both of the practice enquiry strands were primarily associated with the moulding medium rather than the mechanical operation of the tooling systems (such as the setting and locking of the pins).

As a result of undertaking this enquiry, the researcher has increasingly recognised the critical importance intimate knowledge of materials has in innovation scenarios involving the production of physical artefacts. On the basis of the current developments in digital fabrication, it is the researcher's view that there is an underutilised potential in the exploration of these technologies due to projects and innovation initiatives being overly focused on the technical aspects of the tools.

The researcher believes that such a focus could result in underutilising the inherent material characteristics and qualities of the fabrication materials as the focus for innovation in digital fabrication (a charge that the researcher also has to concede to).

It is perhaps relevant to reflect on Negroponte's vision (1996) of how de-materialising of physical products and services was needed to fully embrace the digital revolution. Perhaps now a need is developing to re-engage with physical materials, particularly to inform new generations of designers and innovators about the possibilities they could explore by developing new ways of shaping materials through new tools developed with digital fabrication technologies.

Some initiatives have sought to highlight the importance of physical material in design and innovation practices. An example of such initiatives is the activities of Material ConneXion (Material ConneXion, 2014). This organisation has established a number of Material Libraries around the world and the researcher visited one of these in Bangkok as a part of the scoping and fieldwork activities. Other organisations, such as Materia (Materia Exhibitions B.V., 2015) and The Institute of Making (Institute of Making, n.d.), are taking similar initiatives. Such developments are very positive, but as yet, such material libraries are still only located in a few locations and their impact might largely be as an inspirational presence to highlight the importance materials can have in innovation process, rather than actual resources for innovators to identify fabrication materials for their projects.

9.1.4 Discussions in Relation to S-curve Theory

During this study, the researcher developed a realisation that S-curve theories could be used as a lens though which the current development in the field of digital fabrication could be seen and understood. While S-curve theory was not covered in the initial contextual review, the core notion of S-curve theory is outlined in the contextual review (see subsection 5.5.1). This text also covers the notion of 'disruptive innovations' (Christensen, 1997) and how this aspect of S-curve theory could be used to explain some of the current developments in the digital fabrication sector.

The following section builds on this contextual work, and, using the researcher's reflections on the work undertaken, concludes with a model that seeks to represent a vision of how these theories can be used as a lens to assess the position of some of the common digital fabrication technologies and make predictions for the environment for independent innovation in this field.

As highlighted in the update to the contextual review, 3D printing has frequently been described as a disruptive technology (McKinsey Global Institute, 2013). Here, 3D printing is proposed as providing the potential for facilitating notions of personal fabrication of general consumer goods. The researcher considers that the current *offering* of low cost 3D printing systems still presents a greater potential as prototyping tools for facilitating innovation, rather than personal fabrication systems for the production of final artefacts or products. In contrast, the researcher readily concedes that more advanced 3D printing technologies are highly likely to impact significantly on a number of industries as a direct manufacturing method with disrupting innovation characteristics.

In this analysis it is important to remember that the S-curve innovation theories presented by both Forster and Christensen only relate to specific technologies' economic performance *as products*. Significantly, these theories do not concern the potential economic performance of technologies as *tools*, in a role of enabling other innovations. In this regard, it is relevant to reflect on particular innovation scenarios which concern technologies that have a high capacity to act as tools for enabling other innovations. In such situations a wider secondary economic impact is perhaps more likely to happen towards the end of these technologies' S-curves, where widespread diffusion occurs. It could be argued that, historically, such innovation scenarios could be seen in the development of machine tools in the first industrial revolution and the emergence of the personal computer in the 1970's and 1980's. The researcher proposes that in both of these examples the impact of these innovations (or groups of innovations) were significant as 'innovation facilitators' rather than end products.

In the process of analysing the current situation regarding digital fabrication technologies, the researcher considers that rather than using Roger's innovation curves, Foster's S-curve model provides a more useful lens of investigation. However, providing a comprehensive assessment of the entire field of digital fabrication technologies in relation to their individual S-curve trajectories would not be possible within the capacity of this study. Instead, some indicative examples of this group of fabrication technologies are selected for discussion to assess their position on the S-curve graph. In this respect, it is critical to highlight that it would be incorrect to describe all the digital manufacturing technologies as a single S-curve and it would also be over-simplistic to chart the current 3D printing technologies as a single curve. All these technologies have different S-curves trajectories dependent on the particular application, industry or material, that these technologies are used in connection with.

As an initial example, FDM (see contextual subsections 5.3.1 and 5.3.30) provides a useful focus. The FDM process is now more than 25 years old and despite currently being the one of the most used ALM principles, no significant performance progress has been achieved in the last decade, either in relation to the building speed or the part quality. Using S-curve theory as a forecasting tool, such a technology would be seen at the upper end of this curve, where this technology is at particular risk of being superseded by other innovations.

As the oldest digital fabrication method, CNC milling presents another useful example to explore through the S-curve lens. This technology has now more than 50 years of history and the scope for achieving significant performance improvements within standard Cartesian CNC milling machine construction is likely to be very limited.

Laser cutting is provided as the final example to generate this S-curve theory model. This technology has an almost equally long history as CNC milling, being first employed in the late 1960's (Bromberg, 1991). In the last decade this technology has become increasingly common with no apparent performance improvement in the standard machine concept. Based on this diffusion and the number of years this technology has been employed, laser cutting could also now be considered as having reached a reasonably advanced stage on its S-curve trajectory.

Based on these examples the researcher has developed a view that a group of digital fabrication technologies (including those listed above) have all now reached a level of diffusion, which collectively provides an extremely fertile environment for innovation, just like the historic examples mentioned above. It can be argued that the characteristics of this environment are particularly beneficial to individual entrepreneurs/innovators due to their widespread availability and the low cost of these digital innovation tools. The output from this environment could be both as incremental innovations, such as performance enhancements to existing fabrication concepts, or as entirely new technologies, which may have disruptive characteristics. Fagerberg, commenting on Schumpeter's work, highlights the variability of innovation over time and location, saying that innovation tends 'to cluster not only in certain sectors but also in certain areas and time periods' (Fagerberg et al., 2006, p.14). The researcher proposes that such a cluster could be identified in digital fabrication, fuelled by the maturing and diffusion of earlier technologies, such as examples listed above (CNC milling, laser cutting and FDM). In this innovation cluster these technologies are now performing the role of tools to enable innovation in a new generation of fabrication concepts.

Below is a diagram that seeks to illustrate this concept. The diagram is a further development, by the researcher, of S-curve theories by Foster and Christensen (1997; 1986). It charts how the S-curves of the three digital fabrication examples collectively provide the condition for an innovation cluster to develop (see Fig. 20).

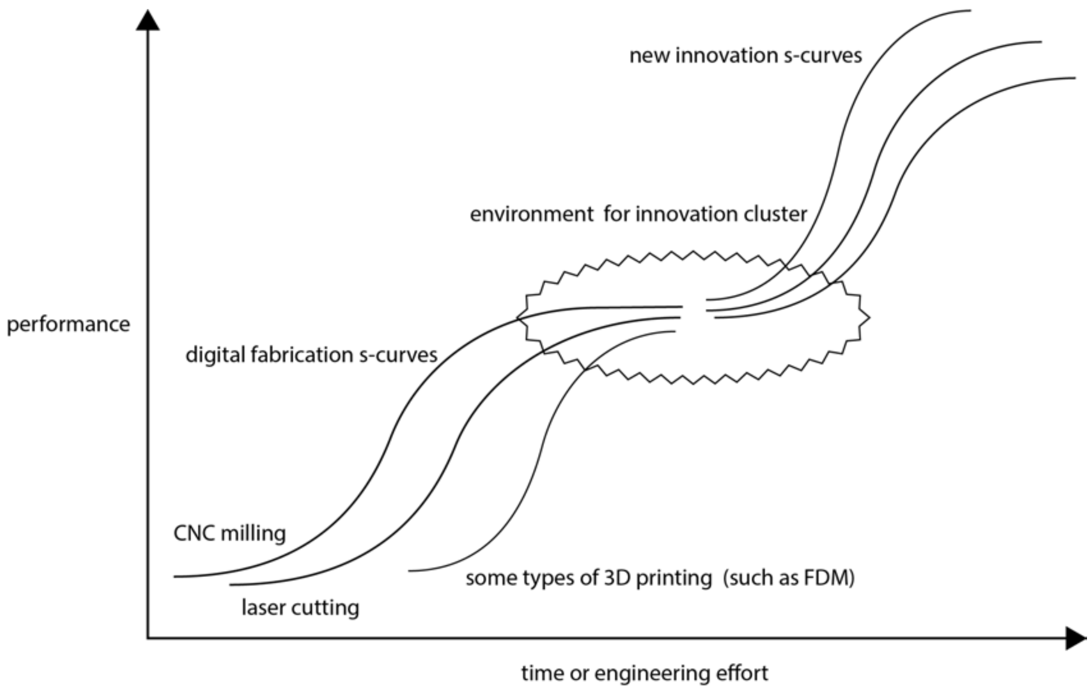


Fig. 124 Illustration of how the diffusion of common digital fabrication creates the environment for an innovation cluster.

Whether such an innovation cluster will enable the RPT concept to flourish and develop its own successful S-curve trajectory will remain to be seen, but the researcher considers that the ability to create the RPT systems in this study is founded within an environment which could be characterised as such an innovation cluster; a cluster which is likely to see many other novel innovations and technologies emerging with their own S-curve trajectories.

9.1.5 Compiling Enabling Factors into an Innovation Tool-Set

As has been highlighted throughout this discussion, one of the central arguments of this study is that it is the *access* to innovation tools that is one of key facilitators for the independent practitioner to innovate. The innovation cluster model presented in the previous section is proposed as the overall environment, which delivers such an increased access to these development tools. But what this discussion also highlights is that a number of other factors and aspects are also identified as have a contributing impact on the innovation scenarios of the practice elements of this study.

While the researcher considers the access to tools as the primary element in this collection of enabling factors, he argues that this collection of innovation enabling factors could best be represented as an *Innovation Tool-Set*, with an Illustration of this model presented below (Fig. 125).

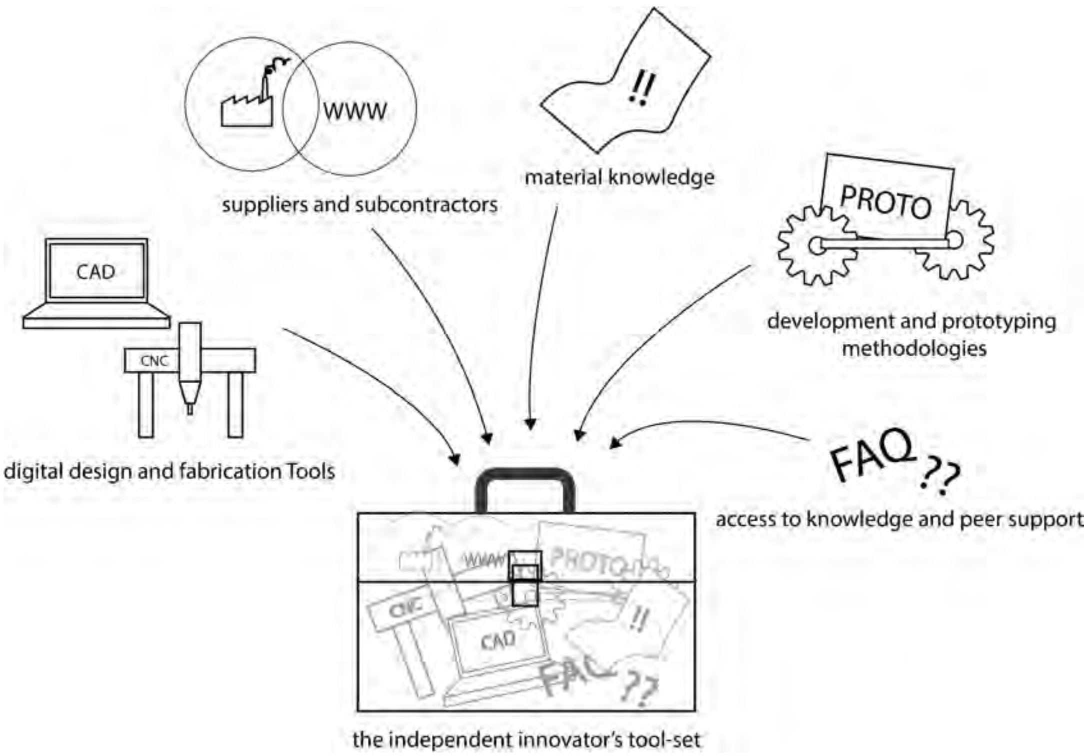


Fig. 125 Enabling factors for innovation - compiled into the notion of an *innovation tool-set*

While the exact composition of the *tool-set* in this model will clearly vary from one individual innovator to another, the researcher proposes the overall structure of this tool-set model reflects the general characteristics of this study's current context (the independent innovator in the field of digital fabrication). However, the 'material knowledge' factor (which is included in this tool-set model) clearly represents obvious variations. The two practice strands of this study certainly concern entirely different moulding mediums with entirely different characteristics. Although the researcher argues that, as an experienced craft practitioner, his general appreciation of material characteristics could be described as being an enhanced level of 'tacit knowledge' (Bolt, 2007) or 'material thinking' (Carter, 2004). The researcher considers that while specific material knowledge is very useful in an innovation scenario, in terms of the tool-set model this element should be understood as a more *general,* enhanced material understanding rooted in tacit knowledge developed from practical experiences.

9.1.6 Shifting Innovation Spheres and Innovator Positions

In analysing the study it is important to reiterate that both of the practice strands have delivered innovation (evidence for this is provided at the start of the discussion chapter). And while recognising the achievement in developing two RPT systems with different technical challenges and target applications, the researcher considers it to be important to note that the two practice strands represent two different innovation *spheres* and innovator *positions*.

In the glass RPT practice strand the researcher operated within his own practice sphere working with materials with which he had intimate knowledge and expertise with. Furthermore in creating the RPT tooling system the researcher used digital design and fabrication tools that he had used extensively in his creative design practice and therefore he could be considered to operate as an *expert* or 'lead user' innovator (Von Hippel, 2005).

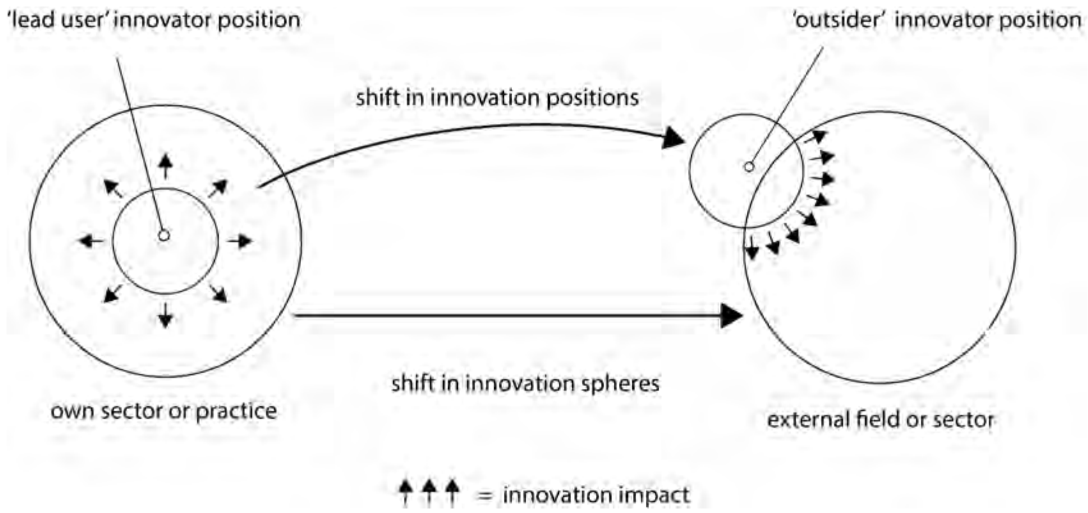


Fig. 126 Figure illustrating shift in innovation spheres and innovator positions.

In the foam RPT investigation the researcher developed an upholstery foam shaping system while being guided by interaction with a local furniture company. In this practice strand the researcher used broadly the *same* innovation tool-set that he employed in the glass investigation, with shared aspects highlighted in the discussion of the glass RPT investigation (see subsection 7.1.7).

While the moulding medium clearly differs in the two practice strands (see the previous subsection for discussion on this issue), the main difference in the two practices strands is that in the foam RPT investigation the researcher can clearly be identified as delivering innovation in a sector which is different from his own practice. The role of the researcher in this enquiry could therefore be described as shifting to an '*outsider innovator'* position (Smith, 2005). This innovator position has been discussed in the contextual review with Pursell and Smith (1994, 2005) highlighting the value of this source of innovation. The researcher has presented a diagram illustrating the *shift* in both the innovation *sphere,* as well as the *innovator position*, (see Fig. 126).

10 Meeting the Aims and Objectives of the Study

The researcher's primary aim with this study was to address the question:

> How can digital fabrication tools and knowledge resources facilitate independent innovation, focussed through an exploration of new applications for Reconfigurable Pin Tooling?

These objectives were identified to address this overall aim:

- To investigate how digitally based tools and knowledge resources can be used in the innovation process of new fabrication systems.
- To investigate particular development methodologies that are characteristic of current independent innovation communities.
- To investigate various RPT concepts and develop iterations of systems established by other researchers.
- To develop and test RPT systems for applications informed by engagement with a regional company, and also within the researcher's own creative practice.
- To contextualise the practical research work within a theoretical framework relating to notions of innovation.

In the following sections each of the separate objectives will be assessed in relation to the work carried out and how each particular objective has been achieved.

- **To investigate how tools and knowledge resources can be used in the innovation process of new design and fabrication systems.**

The contextual review was carried as an initial response to address this objective, with a specific focus on identifying examples of individual practitioners that operate in the field of digital fabrication

The practice elements of this research were also firmly focused on investigating these aspects, and the results have been documented throughout the thesis. While the practice elements of this research remained entirely focused on the RPT concept, the researcher considers that the findings of this study can be more broadly generalized in terms of innovation through the use of digital design and fabrication technologies.

From the outset, knowledge resources, particularly in the shape of peer support via on-line forums and networks, were expected to impact strongly on innovation scenario in the practice elements of this study. However as the development of the RPT systems progressed such online resources seemed to be less relevant and peer support in this study was predominately explored through face-to-face interaction, especially during a CNC building workshop (chapter 7.2.6), which was organised by the researcher.

- **To investigate development methodologies that are characteristic of current independent innovation communities.**

This objective was investigated through both of the practice enquiry strands: the developments of both RPT systems were developed with prototyping and development approaches inspired by those typically associated with current sub-cultures such as the Maker Movement and Hacker communities, and reflect the approach that the research uses as a individual designer maker within his own creative practice. The characteristics of these approaches are discussed throughout the thesis in relation to the practice elements (i.e. they are driven by an iterative 'hands on' development method, rather than being driven by the application of theoretical knowledge to a practical situation).

Furthermore, in relation to the methodological aspects it is relevant to highlight the work that the researcher undertook as a part of this study in order to develop a new format for a research journal operating on IOS devices (described in chapter 6.3 and 11.3). The development of this tool was heavily influenced by notions of reflection both in, and on, action (Schon, 1983).

- **To investigate various RPT concepts and develop iterations of systems established by other researchers.**

The contextual review provided the researcher with comprehensive knowledge of prior work on the RPT concept. However, in the process of establishing the two new RPT systems the researcher found relatively little use, in technical aspects, of the RPT systems developed by others. However, the part of the contextual review, which was focused on prior work on the RPT concept, did serve to inform the researcher of the concepts which had *not* been entirely successful and therefore guided the researcher to explore other options with his RPT systems.

- **To develop and test RPT systems for applications informed by engagement with a regional company, and also within the researchers own creative practice.**

The development of the foam RPT system was carried out by the researcher but guided by consultation with a small local furniture design company, MARK Product. The glass RPT concept was explored through the researcher's own creative practice. This practice stand explored factors that facilitate individual practitioners to develop new tools and tooling applications, equally how such new tools may be explored through the production of new artistic outputs. This aspect of the study also enabled an overall investigation or how tools and development approaches established within a personal innovation sphere can be applied in other sectors.
While both systems underwent significant testing, specific objectives for testing the foam system were developed and structured in two stages, Key stage 1 and Key stage 2. In Key stage 1 the testing was an integrated part of the development process of the RPT system and based on action research methodology with the results of the tests guiding alteration and improvements of the system. The Key stage 2 tests were carried out with the foam RPT system in the most completed state of development with no further alterations being implemented during these tests to ensure controlled conditions in which an assessment of the performance of the system was carried out.

- **To reflect on the practical research enquiry and contextualise the study within a theoretical framework**

An initial theoretical basis for the research was established thought the contextual review, with the researcher focusing on an approach to the study on a 'soft technological deterministic' stance (Chandler, 2000). Additional theoretical contextualising was introduced through an update on the contextual review in subsection 5.5.1. Insights have developed particularly in relation to theories concerning technology S-curves and further reflections on this theory are provided in the discussion (section 9.1.4). In this subsection the researcher presents a modified theoretical model which is proposed as a way of mapping the trajectory of some current digital fabrication technologies and thereby contextualising the innovation environment in this sector.

Through analysis and reflection on the activities undertaken and knowledge gained from interacting with the local business, the researcher also proposes the concept of an *innovation toolset;* comprised of primary, (identified as the access to innovation tools) as well as *supporting* factors (identified as: prototyping methodologies, supplier networks, material knowledge and access to knowledge/support resources).

11 Contributions to Knowledge

Broadly the contribution to knowledge of this research is that as an independent innovator, the researcher developed two novel RPT systems that allow new forms of creative work to be produced. The study has provided useful and relevant information that other innovators or practitioners can build on to develop RPT systems of their own. Through the study the researcher has demonstrated that the digital tools and other resources that are now available to independent practitioners create new opportunities to innovate in their field of practice and to shift this innovation into other sectors beyond their own practice sphere.

The following subchapters summarise more specific knowledge contributions from this study within separate categories, including: artistic and sector contributions, technical contributions, contributions to research methods and conceptional /theoretical contributions.

11.1 Artistic and Sector Contributions

In addition to academic knowledge contributions in fields including innovation theory and design/craft practice, this research is mainly relevant to two other sectors: small scale furniture production and applied art/craft practice. Contribution to the applied art sector is more arguably more prominent and evidenced by high level of disseminations listed in subsection 7.1.7. And while the contextual review did identify another example of the RPT concept being used to shape glass (Weinstein, 2012) the particular glass RPT concept developed through this study is novel in terms of the technical format and specific application (the production of bowls). The creative output developed on the basis of the use of this tool provides evidence of an original knowledge contribution. The two bodies of creative work developed on the basis of the use of the glass RPT system, the *Pin Bowls* and the *Orbit* series of bowls constitutes novel approaches in terms of technique and artistic response to the possibilities presented by the RPT concept. The peer recognition the pieces received through selection for high level exhibition venues (listed in subsection 7.1.7) along with the piece being acquired for the Craft Council's permanent collection, is supporting evidence for this work being a significant contribution to the field.

While the study's potential impact on the furniture sector is (as yet) less evidenced, further development of this aspect over the coming years aims to provide more specific evidence of original knowledge contribution as well as also commercial impact.

11.2 Technical Contributions (in terms of RPT)

While some of the technical solutions developed both in the glass and the foam investigation may not constitute original contributions of knowledge in isolation (separated from the RPT concept), as a collection and within the context of RPT the researcher contends that they do represent new and significant knowledge. The specific technical contributions in relation to each of the practice strands (glass and foam) are summarised below.

In order to successfully develop the glass RPT system a number of innovative technical solutions were established through this practice enquiry, these include:

- The overall glass RPT system format
- *Selected pin* tooling approach
- The individual pin holding bracket (using the *glue gun* principle)

In regard to the foam RPT system, the researcher contends that this RPT application is an entirely novel concept. In this practice strand the researcher developed a complete RPT manufacturing system with integrated digital control scripting, and just like the glass investigation a number of innovative technical solutions were established in the course of creating this system. The list of contributions to knowledge in terms of technical solutions from the foam moulding practice strand includes:

- The overall foam RPT moulding concept
- The spring based holding/locking plate
- The foam holding pin tips
- The approach of setting both pin units together
- RPT rail system and tilting concept

Overall the researcher argues that many of the technical RPT solutions could provide the foundation for innovation for other RPT concepts beyond the foam application and are thereby generalizable beyond the specifics of the applications established as a part of this research.

11.3 Contribution to Research Methods

This contribution is centred around the development of the database system through the development of FileMaker templates and particular use of these in the process of documenting the practical investigations.
Practice-based research, can present challenging situations for data recording and researcher presents this tool as an effective tool for capturing multi-modal data from such research situations. More specifically a capacity to facilitate and record increased reflection both *on* and *in* action (Schon, 1983) – while also gathering empirical and circumstantial data. Overall this tool has the capacity for an effective and rigorous recording of practice based research
While many other practice-based researchers have employed the use of databases in their work, such as (Bunnell, 1998), the particular combination of design, format and use of the data templates developed by the researcher in this study is novel.
The researcher has presented this research tool in a number of presentations and talks at venues including: International Ceramic Centre, Kecskemét, Hungary, Oct 2013, *Glass Boston,* Massachusetts Institute of Technology, Boston, US, June 2013 and the Centre for Information Technology and Architecture, Copenhagen, May 2013.
This tool has also been successfully utilised in other research projects undertaken by the researcher, and documented in papers including Jorgensen and Matthias (2013). Through this dissemination the researcher has received considerable interest from other researcher in this research tool.

11.4 Conceptual and Theoretical Contributions

Whilst this study has been rooted in practice-based investigations, the researcher argues that some conceptual knowledge contributions have also been delivered by this research.

These knowledge contributions are focused around notions of tools as facilitators for innovation. In this regard, the researcher has proposed a S-curve model to illustrate his interpretation of the innovation opportunities that are being presented by the growing maturity and diffusion of a number of digital fabrication technologies' S-curves to form an innovation cluster.

Equally, as a concluding insight of this study, the researcher presents a concept which proposes that a number of factors can be complied into a particular *innovation tools-set* that enable the individual practitioner-innovator to *shift* from a personal innovation sphere to take the role as an 'outsider innovator' – thereby impacting on fields and sectors beyond a personal practice (Smith, 2005). This concept is claimed as the central conceptual knowledge contribution from this study. The argument for this claim is provided in the discussion chapter with evidence provided through the descriptions and reflections of the innovation process in the two practice strands of the study. The argument is supported further by the results of the testing of the foam RPT system and by the interview with the local industry partner, MARK Product (subsection 8.1).

12 Conclusion

Scholarly literature suggests that innovation occurs in certain waves or clusters which are dependent on sector, conditions and location (Fagerberg et al., 2006). Indications are that since the first industrial revolution opportunities for independent inventors and innovators to engage in particular sectors have varied significantly over time (Jewkes et al., 1969). This study concludes that, currently the conditions are particularly favourable for the independent innovator operating in the context of digital fabrication.

This study is centred on two practice enquiries which both provides evidence for the capacity of the independent practitioner to delivery innovation in, or through, digital fabrication technologies.

In one of these enquires the researcher developed an innovative RPT concept for shaping glass bowls and used this system within his own creative practice to create a number of pieces. The originality and quality of these pieces is evidenced by the work being selected for numerous exhibitions at leading international venues, acquisition by public collections and numerous sales to the general public. In this investigation the researcher's position could be described a 'lead user' innovator (Von Hippel, 2005, 1986) – as he used his knowledge as a advanced *user* of (digital fabrication) tools to develop a glass moulding system within his own practice sphere.

But as well as operating within his own practice, this study also included a strand of practice where the researcher developed a RPT system for shaping upholstery foam. The researcher (with his background in ceramic design and craft practice) therefore contributed with innovation in a sector *beyond* his own practice and thus operated in a position which could be described as an 'outsider innovator' (Smith, 2005).

Both of the RPT concepts developed in this study were established through the development of a number of technical solutions, which have solved some key issues that have long been associated with the general RPT principle. The contextual review revealed how particular key technical challenges have been the focus of large and well-resourced research projects (Munro and Walczyk, 2007), but still not resulted in actual applications and manufacturing processes. The researcher argues that this achievement illustrates that the individual practitioner (or small business) in some cases has a better capacity for developing solutions to certain problems and thereby also have a particular capacity for innovation.

Having established evidence for the capacity and value of the independent practitioner to innovate the question is, what are the key facilitating factors that enable this innovation?

One of the central arguments of this study is that it is *access* to innovation tools that is the primary enabling factor for the independent practitioner to innovate. More specifically in this study it is the maturing and diffusion of earlier generation digital design and fabrication tools that facilitates independent innovators to develop new fabrication technologies and manufacturing applications. This argument is evidenced through the description and reflections on the innovation process in both of these practice stands. Furthermore the researcher has presented a model which shows how technology S-curves of a number digital fabrication technologies converge (in their diffusion stage) to create a current fertile environment that supply the tools which help to enable such independent innovation. Specific tools, which have been critical in the creation of the RPT systems in this study, include laser cutters, FDM 3D printing and powerful software tools such as Rhino Grasshopper.

But as well as tools the researcher also identified a number of other factors and aspects, which also had a facilitating impact on the innovation scenario in the practice enquires of this study. These include utilisation of the material characteristics of the fabrication medium. A particular structure of suppliers and subcontractors based an combination of on-line and local/physical companies is also considered as contributing factor, and this business environment has been referenced to previous notions of 'flexible specialisation' (Kumar, 1995). Equally, particular development and prototyping approaches that are associated with current independent innovation subcultures, such as the Maker Movement and Hacker communities, were also investigated and identified as a contributing factor. In short, these approaches are focused on innovation and development through practical prototyping rather that theoretical planning.

The researcher argues that all of the above aspects can be complied into an *innovation toolset* that has a specific structure that reflects the context of this study. This model is presented in the discussion chapter (see Fig. 125).

Equally, the researcher argues that the innovation scenarios in the two practice strands illustrates how individual innovators can *shift* from operating within a personal sphere of practice to deliver innovation in field or sector beyond their own. The researcher has created a graphical representation of this concept (see Fig. 126 in subsection 9.1.6). This model also illustrates that in the independent innovator in making the shift in these spheres of impact also shifts in terms the innovator position – from an *expert*, or ‘lead user’, position to that of and ‘outsider innovator’ (Smith, 2005; Von Hippel, 2005).

As a *concluding insight* the researcher argues that it is the *innovator toolset* described above that enables the independent practitioner to make the specific *shift* from an individual innovator practice to operate effectively other sectors in the role as the *outsider innovator*.

As a closing remark the researcher would like to reiterate the value of using innovation, which has been developed within an individual practice, as the source of innovation in an external field and the concept of using an *innovation toolset* that has been established within this practice (complete with development tools, prototyping methods, supplier networks and material knowledge), as an effective way of transferring innovation impact to other sectors. The researcher argues that this model could be used to encourage and foster future independent innovators operating beyond the technical and contextual particularities of this study.

13 Suggestions for Further Work

The researcher believes that this study has developed knowledge that could contribute to the foundation for a number of further investigations. These research opportunities are summarised into separated aspects, which are listed in the following subsections.

13.1 Technical Aspects

With two novel productions systems having been developed in the course of this study, there are ample opportunities for further research in terms of technical advancement.

The results of the tests carried out on the foam RPT systems indicates that some aspects could be improved in terms of the system's performance, these include production consistency and accuracy in relation to digital design input. However, with a relatively small testing range the extent of these issues is yet to be determined, and a larger test study is required to investigate these issues fully. Overall, the foam RPT system requires further development and refinement, with research required in the process of development and testing of system iterations. In order to ensure that the foam RPT system has commercial relevance, this work should be carried out in close consultation with relevant industry partners.

The Glass RPT system is arguably much more resolved than that of the foam system. The researcher employed the glass system extensively in his creative practice with commercially viable outputs. The individualised pin-holding bracket has proved very successful and that aspect has resulted in a system that is very usable. This situation means that there is a good basis for the researcher to continue to explore the creative potential of the system. Although the system is now functioning well, extending the capability of the system further is still a possibility. A customised CNC setting station is one of the features that the researcher is planning to implement.

13.2 IOS Database Templates

The IOS research journal concept proved a very useful research tool in this study. The researcher has received significant interest from other researchers in this area of the study and believes that the concept has the potential to be applied in many other fields and research situations.

The FileMaker Go environment in which this research journal template operates is free, and templates can be readily shared with other users. It is the researcher's intention to make some of the templates, developed during this study, available for others to utilise, explore and develop further. New studies are needed that focus specifically on the use of this research tool to guide further development and work.

13.3 Conceptual and Theoretical

It should be evident from this thesis that the theoretical and conceptual issues which impact on the subject of independent innovation are many and varied. Theories concerning technological determinism, technology S-curves, innovation environment and innovator roles, all present different theoretical and conceptual lenses through which the current innovation environment could be observed through.

Equally, the current environment that is presented to individual independent innovators remains fluid. Significant changes have affected this environment during the course of this study and the researcher considers that further significant changes will impact over the coming years, particularly through further diffusion of digital fabrication technologies.

In subsection 9.1.4 the researcher proposed a model to explain the current positions of certain digital fabrication technologies based on S-Curve theories. The researcher intends to develop this work further and believes that first-hand observations from active (and reflective) practitioners could provide valuable insights to compliment commentary provided by other observers and non-practitioner researchers.

The researcher also intends to pursue further studies into the wider concept of tool-making. There is a substantial amount of innovation literature covering tools as products, but far less research seems to have been undertaken in terms of mapping the impact that tools and tool-making has as facilitators for innovation.

13.4 Artistic

The glass pieces produced as a result of this research clearly illustrate the artistic potential of the RPT concept. The practice strand focussed on exploring glass with the RPT concept has so far resulted in two distinctive series of pieces, however, it is evident to the researcher that this concept has the potential to be explored much further.

The artistic potential of the foam RPT system was far less explored than the glass system. Although some close consideration was expended on the design and construction of the initial range of prototype seats, the artistic potential of this concept is still largely unexplored. As many of the technical aspects of the foam system also requires more work (as highlighted above), there is an obvious opportunity for improving the technical aspects in connection with explorations of the creative potential, or to use artistic ambitions to inform the development of the system.

In this work, the researcher recognises there is significant potential in collaboration with other designers and companies, thereby extending the impact of work that was initially driven by independent innovation.

Glossary

3D Modelling:

A concepts almost identical to that of Computer Aided Design (CAD) although the term 3D modelling more specifically describes the process of designing directly in a virtual three-dimensional environment rather than through two-dimensional projections.

3D Printing:

Essentially the same as Additive Layer Manufacturing (ALM) — a method of generating physical artefacts from computer data through the printing of multiple layers of cross-sections.

ALM (or AM):

Abbreviation of: Additive (Layer) Manufacturing — a manufacturing concept where physical artefacts are constructed by stacking layers of cross sections onto of each other through digitally operated machines. The term ALM is used to describe a large group of technologies which all adopt various approaches within this principle. The ALM term is increasingly replacing the term Rapid Prototyping (RP) as the overarching description for digitally driven additive manufacturing technologies.

Boolean:

A general principle in computer modelling, where an expression can only have two possible values (true or false). The term is also used to describe a particular set of tools in 3D modelling software, where one form is used as a tool to subtract one shape from another.

CAD:

Abbreviation of Computer Aided Design — the use of computer based programs to draw and model designs in either two or three dimensions.

CAM:

Abbreviation of Computer Aided Manufacturing — the process of using computer software to operate machine tools, such as CNC milling machines. The software that generates the tool-path and numerical code, which controls CNC equipment, is known as CAM software.

Cartesian:

A coordinate system with X, Y and Z axes, named after the French mathematician René Descartes ('Cartesius' in Latin) — who first developed the system.

CC BY-NC-ND 3.0:

Abbreviation of 'Attribution-Non Commercial-No Derivatives 3.0 Unported' — a Creative Commons licence allowing the free sharing and reproduction of material under certain conditions (Creative Commons, n.d.).

Closely Coupled Matrix:

A variation of the Reconfigurable Pin Tooling concept using an array of pins closely stacked together to form a solid tooling or mould surface.

CMF:

Abbreviation of Combustion Modified Foam — a general use, budget upholstery foam, unusually supplied in a light blue colour.

CNC:

Abbreviation of Computer Numerical Control — the process of operating machinery via a digital instruction set, usually using a classic Cartesian coordinate system with X, Y and Z axes.

Definition:

A Rhino Grasshopper script (visual programming).

DLP:

Abbreviation of Digital Light Projection — a relatively new ALM technology using a generic digital light projector to create objects by curing layers of resin.

Equally Spaced Matrix:

A variation of the Reconfigurable Pin Tooling concept using an of array of pins equally spaced. That relies on the stiffness of the moulding medium to be suspended between the pins.

FabLab:

Abbreviation of A Fabrication Laboratory — a concept for a community workshop with facilitates for users to carry out personal fabrication (and innovation) through digital fabrication technologies.

FDM:

Abbreviation of Fused Deposition Modelling — a variant of Additive Layer Manufacturing (or 3D printing) by using a heated nozzle to extrude plastic filament in order to construct physical artefacts through numerous layers.

FOSS:

Abbreviation of Free and Open Source Software.

G-Code:

A numerical programming language usually employed in CNC machining.

Grasshopper:

A visual scripting environment for the Rhino 3D CAD modelling software created by David Rutten.

GUI:

Abbreviation of Graphical User Interface — a way of interacting with a computer through graphical representations of functions rather than textual or numeric commands.

Homebrew:

A term used as a part of the title for a Californian DIY computer forum in 1970's and 80's (The Homebrew Computer Club). This term has since been used to describe CNC projects that are carried out in a DIY context rather than by commercial companies.

IOS:

Abbreviation of iPhone Operating System — the basic operating system used in Apple iPhones and iPads.

IP:

Abbreviation of Intellectual Property — an overarching legal description for the realisation of an idea. IP includes designs, works of art, inventions and literature. Patents, copyrights, Trademarks and Design Rights are all methods for protecting the commercial interest of IP.

M Code:

Abbreviation of Machine Code — a set of computer instructions frequently used in CNC machining in the same role as G-Code.

Maker Movement:

A general term for a subculture of DIY enthusiasts. The terms probably originated from the *MAKE* magazine and associated Makerfairs.

NURBS:

Abbreviation of Non Uniform Rational Basis Spline — a mathematical way of describing a curve or surface. In this representation, a curve (or surface) is described as a continuous 'smooth' path, with control points directing the trajectory of the curve or surface.

Oligopoly:

A commercial situation where a market is dominated by a small number of companies.

Open Source:

A communal development and licensing model, initially established in the field of computer software and programming. This model is based on development knowledge (source code) made ‘openly available’, thereby enabling anyone to contribute to the development process. The Open Source model has now been adopted for many other fields, including design, science, engineering and medicine.

PHP:

A computer coding language frequently used for server side web applications.

Reflex 40:

A high-grade furniture/upholstery foam. The number (40) indicates the density of the product (40kg per cu/m).

RepRap:

Abbreviation of ‘Replicating Rapid Prototyper’. The RepRap project was initiated at the University of Bath and lead by Adrian Bowyer as a research project aimed at exploring notions of machine self reproduction. The project resulted in the creation of a low cost and open source FDM machine concept.

RepStrap:

A derivative design of a RepRap machine.

Rhino 3D:

A commercial NURBS based three-dimensional Computer Aided Design (CAD) program.

RP:

Abbreviation of Rapid Prototyping — an early general term used to describe a group of digitally driven prototyping approaches. Terms such as 3D printing and Additive Manufacturing are now starting to supersede the use of the RP term as more accurate descriptions for these technologies.

RPT:

Abbreviation of Reconfigurable Pin Tooling — a flexible tooling concept based on the use of a matrix of individual elements (pins) which can be set and locked to perform a tooling function but remains repositionable to represent other forms or tools.

RT:

Abbreviation of: Rapid Tooling — a term used to describe moulds developed or fabricated via digital manufacturing.

SAE 316:

A steel alloy which is also known as ‘Marine Grade Stainless Steel’. This alloy contains 16-18% Chromium and 10-14% Nickel, which facilitates a higher level of corrosion resistance (in a marine environment, for example) than standard stainless steel (SAE 304). The corrosion resistance of 316 stainless steel also makes it well-suited for constructing tools and moulds for kiln forming glass.

SLA:

Abbreviation of Stereolithography — one of the first ALM methods developed that was based on a concept where CNC controlled lasers cures liquid resin layer-by-layer, resulting in physical three-dimensional forms.

Slumping:

A methods of forming glass though the use of heat and gravity. This process can be used either *over* or *into* a refractory mould. The process is based on the use of single-sided moulds, relying on gravity to force the glass against the mould surface (or through the aperture ring).

STL:

A file format developed by 3D Systems for the transfers of 3D object data for use in digital manufacturing systems, 3D printing (or ALM) systems in particular. The term initially referenced 'Stereolithography', which was an early form of ALM, but now STL more commonly denotes 'Standard Triangulated Language' or 'Standard Tessellated Language'. This is a reference to the characteristic triangular surface element, which is used to construct the surface of objects in this file format.

Toolpath:

The movement that a machine tool travels to perform a machining operation, for example the pattern that a CNC operated cutting tool would move to grid away material.

Visual Scripting:

Also known as 'Visual Programming Language' (VPL). A programming environment that enables the user to create computer software programs though the use of graphical representations of functions rather than by textual code.

VPL:

Abbreviation of: Visual Programming Language.

WYSIVYG:

An acronym of what-you-see-is-what-you-get. This term is used to describe an interface of a computer program that provides the user with a close simulation of the final outcome (such as a printed document or web page).

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1 Appendices

1.1 Dissemination and Exhibitions

1.1.1 Craft Code 011

Location: Wills Lane Gallery, St Ives, Cornwall,

Dates: 11/9/2011 to 30/10/2012, Photo Credit: T. Jørgensen, 2011.

TAVS JØRGENSEN

Tavs Jorgensen is a research fellow at the Autonomatic Research Group, University College Falmouth. Jorgensen arrived in Britain in 1991 after completing a 4-year pottery apprenticeship in his native Denmark. He studied 3D Ceramic Design at Cardiff Institute from 1992 to 1995. Following his graduation he established his own ceramic design consultancy, working for some of the world's leading tableware companies. In recent years he has increasingly focused his practice on research, in particular exploring how new models of creative practice can be developed on the basis of digital technology tools. Jorgensen is a regular visiting tutor on the Ceramic and Glass course at the Royal College of Art, London and is also a guest lecturer at leading international universities and colleges.

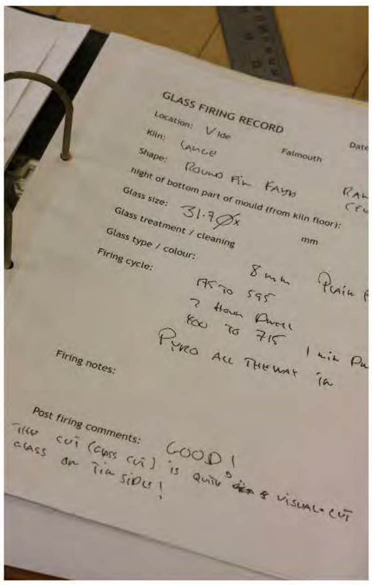
Over the last couple of years Jorgensen has started exploring a novel moulding method called 'Reconfigurable Pin Tooling'. The concept which is also described as 'Universal Tooling' is broadly the same principle as the one used for the popular 1980's Pin Screen toy, which consists of a set of perforated screens in which an array of nails is inserted, enabling impression of hands, face and objects to be made. However, the history of this concept dates back much further. The principle has been explored for at least 150 years as a reconfigurable moulding apparatus capable of producing an infinite variety of shapes.

But despite many attempts by inventors and engineers over the years the technical challenges associated with the concept have never been fully resolved and a real 'killer application' has so far eluded the inventors. In many ways it has remained the ultimate but also unobtainable tooling concept. However, digital technology has in recent years provided increased access to tools which enable new applications and creative approaches to be explored with this production concept.

The work in the CRAFT CODE - 011 exhibition is the first collection of glass pieces from Jorgensen's creative investigation of this method of making.

PIN BOWL 2011
FLOAT GLASS
18 X 46 X 46 CM

TAVS JØRGENSEN



WILLS LANE – ST IVES – CORNWALL TR26 1AY – TELEPHONE +44
EMAIL: INFO@WILLSLANEGALLERY.CO.UK – WWW.WILLSLANEGALLERY.CO.UK
WEDNESDAY–SATURDAY 10.30AM–5.30PM SUNDAY 11AM–4PM OR BY APPOINTMENT

EXHIBITION 11TH SEPTEMBER – 30TH OCTOBER 2011

THE WILLS LANE GALLERY

CRAFT CODE – 011 – NEW WAYS OF MAKING – GARY ALLSON AND ISMINI SAMANIDOU – WOOD, PAPER, WEAVING – KATIE BUNNELL – CERAMICS – TAVS JØRGENSEN – GLASS – DRUMMOND MASTERTON – METALWORK

WILLS LANE – ST. IVES – CORNWALL TR26 1AY

'Ultimately the computer is a means for combining the skilful hand with the reasoning mind. Our use of computers ought not to be so much for automating tasks as for abstracting craft.'
Malcolm McCullough, *Abstracting Craft* 1996

'The more we forbid ourselves to conceive of hybrids, the more possible their interbreeding becomes [...]'
Bruno Latour, *We Have Never Been Modern* 1993

It is perhaps ironic that the digital and the analogue are so often discussed in binary opposition to one another. The more present that digital becomes, the louder the discourse becomes in its pros and cons relative to analogue, when quietly, hybrid practices are developing. The present moment signifies a point of change, a desire for discourse on craft that does not simply create dichotomies that prevent understanding of processes and of making.

CRAFT CODE - 011 – NEW WAYS OF MAKING explores the potential for experimentation and reappropriation, using digital technologies with traditional skills to create hybrid processes that create new contexts for craft production. These designer-makers reflect the move towards the postdigital in the hybridity of processes, playfully subverting expectations of 'digital' and 'handmade', but always remain connected to materiality.

These hybrid processes of making have emerged from the Autonomatic research cluster at University College Falmouth, where human-machine interaction, experimentation and innovative thinking produce diverse work connected by the discourse around craft and digital technologies. Combined with traditional skills and materials, these digital tools can create new modes of sustainable practice which seek to give the designer-maker greater autonomy.

In the 1970s, industrial CNC (Computer Numerically Controlled) machines were developed that allowed the production of 3D things by entering numerical co-ordinates defining height, width and depth. From the 1980s onwards, computing technology evolved and democratised, allowing complex 3D objects to be designed on a 2D computer screen, but few had access to ways of making these objects real. Now, a new conceptualisation of tools and process is emerging.

The physicalization of the digital is produced by challenging and interrogating these tools, and reflects a wider movement towards this reification of digital technologies as a natural progression from on-screen to real life from other kinds of digital media. What would have previously only been possible in 3D digital design on a 2D computer screen, developments in Rapid Prototyping and CNC allow objects to break out of the frame of the computer screen, creating new possibilities in making 3D objects that were previously only conceivable in 2D. Ultimately, as McCullough suggests, using digital technology is not about automation, or an anonymous computerised aesthetic, it is about intellectual investigation and creative manipulation, using hand and head to develop tools that give a new context to modes of production.

The autonomous hand of the maker is both visible and invisible in these new ways of making. A playful relationship between ideas of hand-made and digital connects these makers. A looping transformation between handmade and digital, blurs through an iterative process of making and remaking. Katie Bunnell's *Bunny Beakers* started as a desire to create a narrative on a drinking vessel. Hand-drawings are scanned to create a digital image that is used to create a silicon mould, wrapped to create a beaker shape, and slip cast in porcelain. Concealing the mould's join by hand-stitching the silicone reveals the hand in the beakers' making, hand-made imperfections and continuous touch inscribed by hybrid process.

This hybrid processing of information to produce different contexts of making is integral to the circularity of process in collaboration between Ismini Samanidou and Gary Allson. Ismini's hand-woven textiles made using traditional fan reed techniques are not flat. Tension in the weave produces a 3D object that is digitally scanned, then output digitally in different materials. When drawn on to paper with a CNC milling machine using pen or brush, they appear to be exquisitely hand-drawn. Using three sets of co-ordinates, a 3D drawing becomes 2D image, demonstrating a sensitive hand-drawn aesthetic that playfully refutes any preconceived notions of digital craft. The CNC milling machine then inscribes the textile weave into Cornish oak. The tactile surfaces of the woven wood are both impossible textile and miniature landscapes.

Drummond Masterton's work in metal is influenced by his refusal to accept the limitations of digital technology's aesthetics. The triangulation of points in space in 3D digital production tends to create a triangulated aesthetic, the process self-evident in the craft object. By understanding this triangulation he is able to break out of it, using triangulation to escape the triangular. Three-dimensional co-ordinates of making machines relate to co-ordinates in real space; fingers travel over the object's surface and continue moving over an imaginary landscape. Drummond talks of the essential hidden haptic element of the hand's intervention of the digital making process, the stopping and starting of the machine, the touching or blowing required that reveal the autonomous maker in the seemingly automated machine.

Points in space are materialised further in Tavs Jorgensen's work exploring the possibilities of 'Pin-Point', 'an array of pins placed in a set of perforated screens in which impressions made from one side are reflected as positive shapes on the other', allowing infinite shapes to be reproduced in kiln-formed glass. This experimental tool allows for different modes of production, that allow, like the others used here, the intervention of the hand of the maker according to desire, to adjust the digital design by hand. The process of making is visible, and integral to the materiality of the object, creating layers of meaning beyond the aesthetic. Tavs' investigations are iterations of process that express a need to find ways for makers to gain more flexibility and sustainability in contemporary craft.

Connected by points in space, place, inversions of process, playful and practical interventions of the hand, a love of traditional skills and the ultimate materiality of production, CRAFT CODE - 011 – NEW WAYS OF MAKING is a reconsideration of contemporary practice.

Jeanie Sinclair

JEANIE SINCLAIR (Research Fellow St. Ives Archive, PhD Researcher University College Falmouth) Her research uses the space between experience and memory to creatively examine how art and cultural practice, past and present, connects individuals and communities, and how memory and identity is performed through space and place.

CRAFT CODE – 011 – NEW WAYS OF MAKING

1.1.2 The Tool at Hand

Location: Milwaukee Art Museum, Milwaukee, US

Dates: 8/12/2011 to 1/4/2012, Photo Credit: T. Jørgensen, 2012

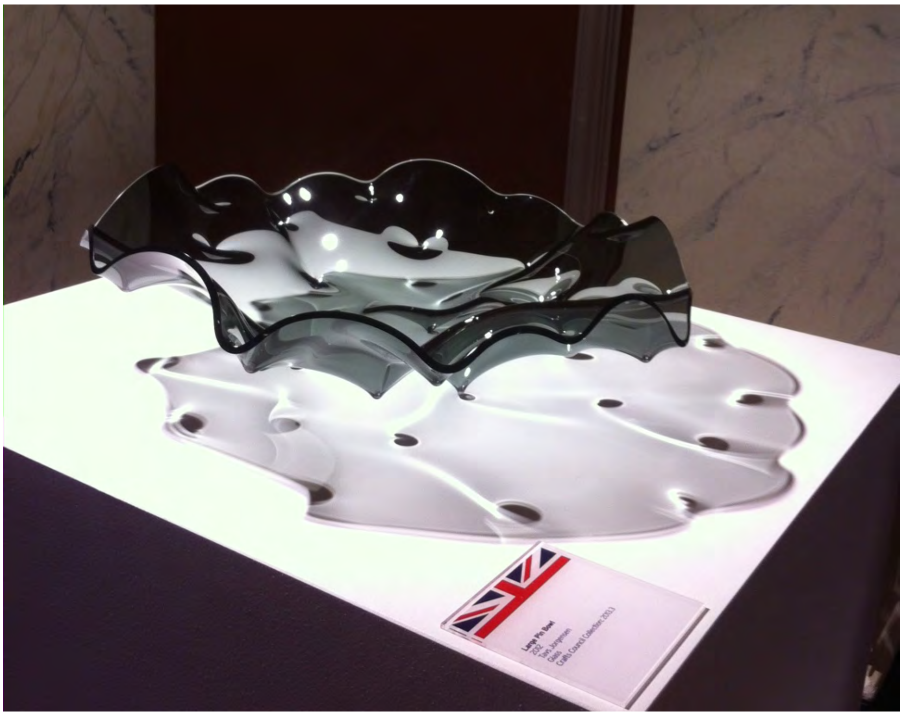
1.1.3 Collect 2012

Location: Collect, Saatchi Gallery, Kings Road, London

Dates: 11/5/2012 to 14/5/2012, Photo Credit: Sylvain Deleu 2012

1.1.4 Best of British

Location: Lancaster House, (Global Business Summit) Stable Yard, London.
Date: May 2013, Photo Credit: Sarah Turner 2013



1.1.5 Autonomatic At Making Futures

Location: Mount Edgcombe, Making Futures Conference, Plymouth
Dates: 26/9/2013 to 27/09/2013, Photo Credit: T. Jørgensen, 2013

1.1.6 Collect 2014

Location: Collect, Saatchi Gallery, Kings Road, London

Dates: 9/5/2014 to 12/5/2015, Photo Credit: T. Jørgensen, 2014

1.1.7 All Makers Now?

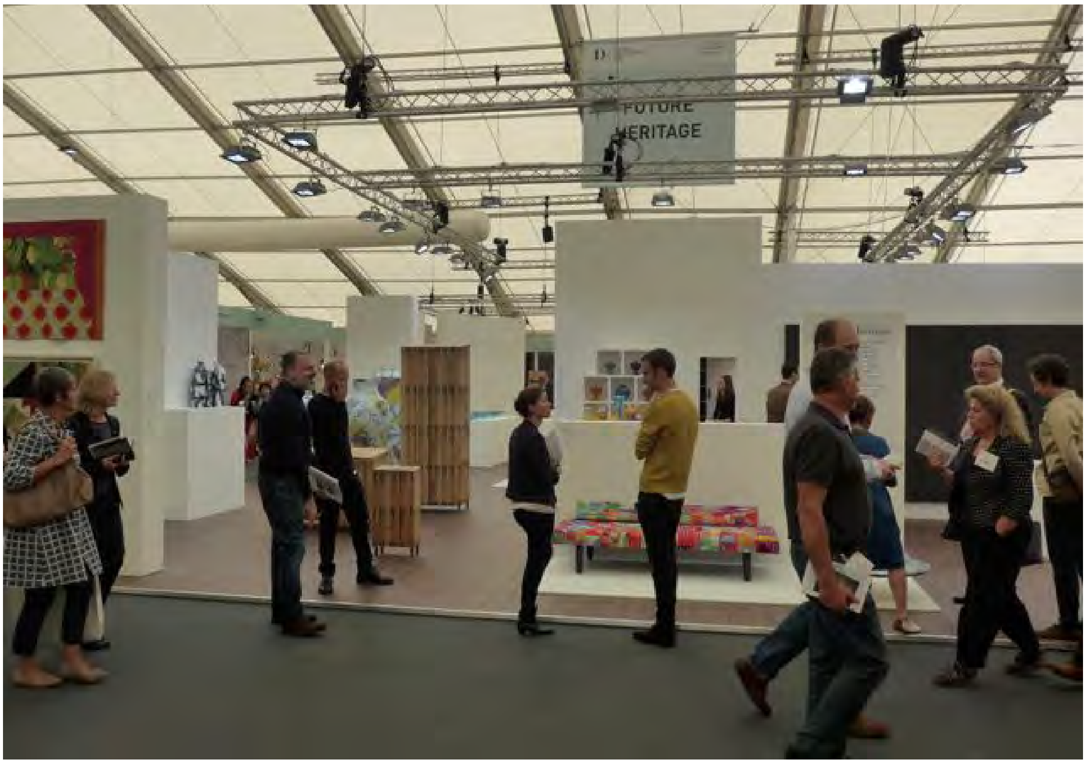
Location: All Makers Now? Conference, Trelissick House, Feock, Truro, Cornwall

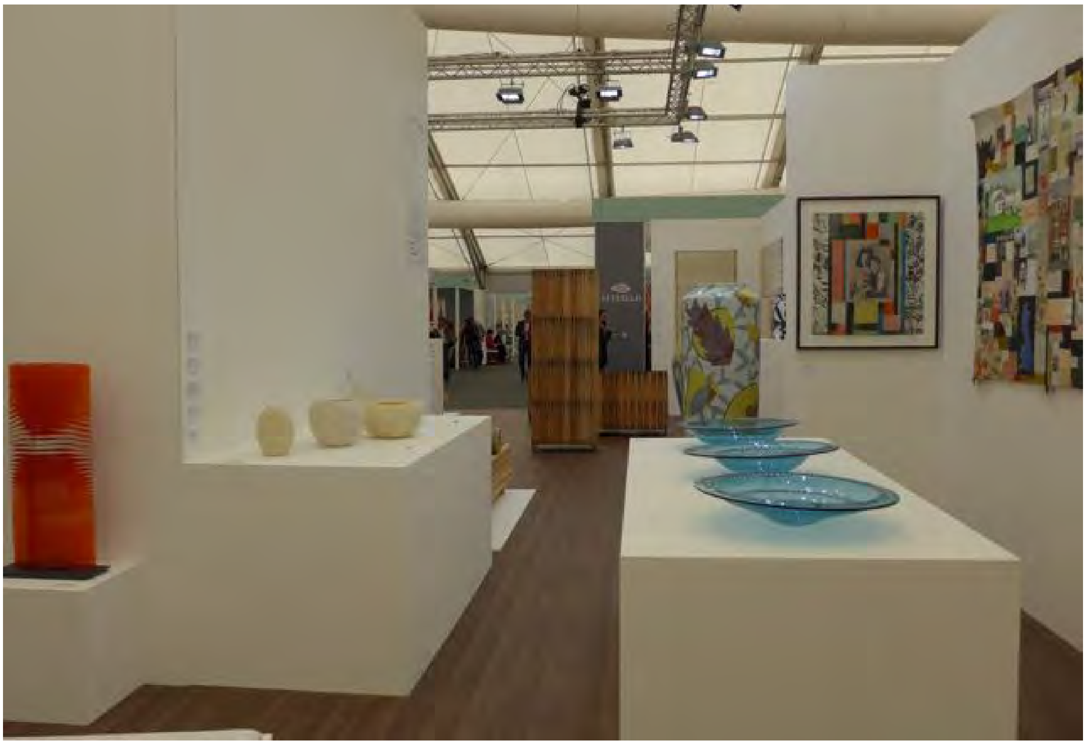
Date: 10/72014, Photo Credit: T. Jørgensen, 2014

1.1.8 Future Heritage

Location: Decorex, Syon Park, London

Dates: 21/9/2014 to 24/9/2014 Photo Credit: T. Jørgensen, 2014



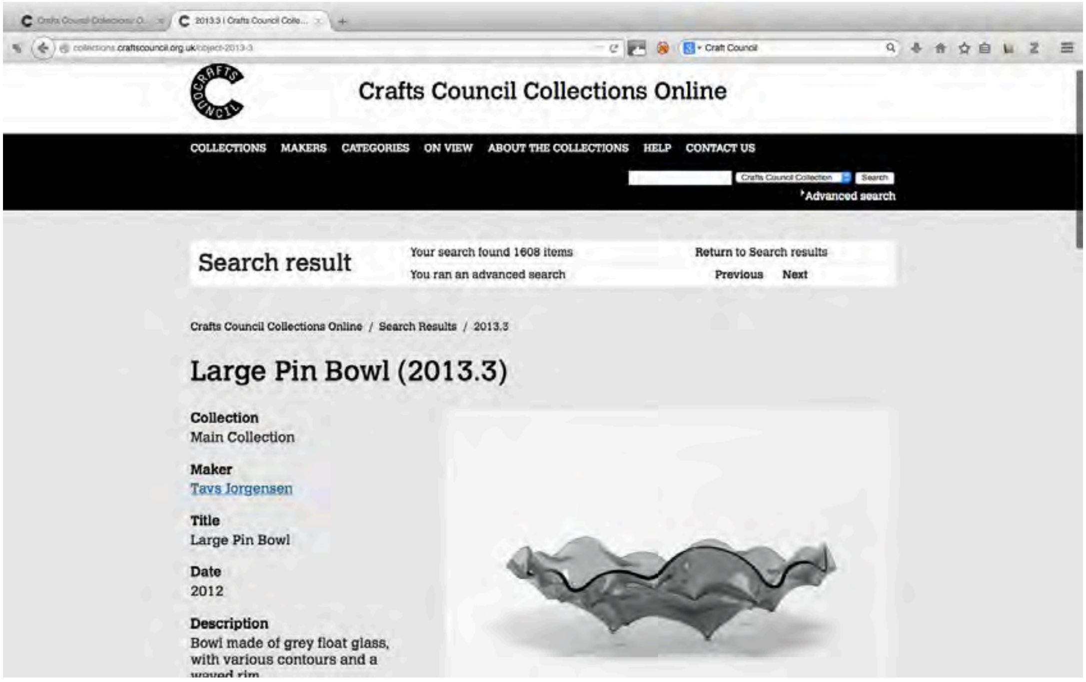


1.1.9 British Design: from William Morris to the Digital Revolution

Location: Pushkin Museum, Moscow, Russia

Dates: October 2014 Photo Credit: Natalia Goldchteine 2014

1.1.10 Glass bowl Acquisition, Craft Council Permanent Collection



From: **Christina McGregor** c_mcgregor@craftscouncil.org.uk
Subject: RE: Documentation for acquisition
Date: 5 November 2013 14:50
To: Annabelle Campbell a_campbell@craftscouncil.org.uk, Tavs Jorgensen tavs.jorgensen@rca.ac.uk
Cc: Petronilla Silver info@willslanegallery.co.uk

CM

Dear Tavs Jorgensen,

Annabelle has passed your enquiry to me and I have checked our Acquisition information for the purchase of Large Pin Bowl earlier this year.

The work was proposed to us as a potential acquisition by Michael Marriott, a member of our Acquisition Advisory Panel. In his proposal Michael summarises:

'Tavs is an unusual maker, with an interesting mixed career, including; ceramic design for industry, academic research, teaching, ceramic & glass craft practice. I think this recent body of work is a very assured and mature outcome of a long period of research looking into digital technologies and how they can be combined and utilised in craft practice.... There is a strong & inevitable interest in digital technology, rarely utilised and incorporated with such clear thinking.'

The Acquisition Panel agreed with Michael's assessment of your work and minuted the agreed acquisition as 'The Crafts Council has a long standing relationship with Jorgensen having worked with him on the One Liner online exhibition. Large Pin Bowl, 2012 was seen as a piece that was reflective of the process of making, focusing on digital technologies and their contemporary practice. Jorgensen's piece Large Pin Bowl, 2012 was purchased for the Collection.'

Best wishes,

Christina

Christina McGregor
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Please note my working week is Tuesday to Thursday

1.2 Ethics

1.2.1 Image Permission Template

Hello

I am PhD candidate at Falmouth University in the UK and the subject of my study is independent innovation through the use of digital fabrication tools.

Your work has strong relevance in the contextual review part of my thesis, and I would very much like to include an image of your work (you will be fully referenced).

The image below has been sourced from online searches, and I would be very grateful if you would respond to grant your permission to use it.
Please could you also let me know the date and relevant photography accreditations (the name of the photographer and date).

Many Thanks

Tavs Jørgensen
PhD Candidate, Falmouth University

1.2.2 Participant Agreement Form Template

FALMOUTH UNIVERSITY

1. Project Title:

The development and application of digitally enabled Reconfigurable Tooling in the context of new opportunities for the independent innovator.

2. Invitation to Participate:

You are being invited to take part in a research project. Before you decide to take part it is important for you to understand why the research is being done and what it will involve. Please make sure that you are clear on you're your participation involves and ask if anything is unclear or if you would like more information.

3. Activity Consents:

I understand that I have given my consent for the following to take place:

- To be interviewed to explore and identify applications for the concept of reconfigurable tooling within my business sector.
- That both video and audio recordings will be made of this interview

4. Data Consents

- I understand that I have given approval for my interview opinions to be published / shown or exhibited in the final report / thesis of this project.
- I understand that confidentiality and anonymity cannot be guaranteed for the information which I have disclosed in the interview.
- I understand that my name and a short description of my business may be included in the final published report.
- I understand and have had explained to me any issues relating to commercial confidentiality for me or the company that I am representing and, if relevant, a Non Disclosure Agreement has been signed.
- Having given this consent I understand that material, once published information cannot be withdrawn from the final report.

I hereby fully and freely consent to participation in the study which has been fully explained to me.

5. Statements of Understanding

I have sufficient information bout the research project, which I have been asked to take part in.

What is going to happen and why it is being done has been explained to me, and I have had the opportunity to discuss the details and ask questions.

6. Right of withdrawal

Having given this consent I understand that I have the right to withdraw from the programme at any time without disadvantage to myself and without having to give any reason.

7. Statement of Consent

I have been provided with information about the research project which I have been asked to take part in.

I hereby fully and freely consent to participation in the study which has been fully explained to me.

8. Signatures

Participant's name (BLOCK CAPITALS): ______________________________

Participant's signature: ______________________________ *Date:* ____________

Principal staff/student *investigator's name* (BLOCK CAPITALS): ______________________________

Principal staff/student investigator's signature: ______________________________ *Date:* ____________

9. Contacts Details:

Principal researcher:
Tavs Jorgensen
Falmouth University, AIR, Penryn Campus, Treliever Road, Penryn, Cornwall, TR10 9EZ T: 01326 253689 Email: tavs.jorgensen@falmouth.ac.uk

Director of studies:
Justin Marshall,
Falmouth University, AIR, Penryn Campus, Treliever Road, Penryn, Cornwall, TR10 9EZ T: 01326 253689 email: justin.marshall@falmouth.ac.uk

Research Support Office:
6th Floor, 272 High Holborn, London WC1V 7EY, T:00 44 (0) 20 7514 9389, E: research@arts.ac.uk

1.2.3 NDA Template

CONFIDENTIAL DISCLOSURE AGREEMENT

Between:

University College
FALMOUTH
Incorporating Dartington College of Arts

And:

Tavs Jorgensen
University College Falmouth University College Falmouth
Design Centre, Tremough Campus
Penryn, Cornwall
TR10 9EZ, UK.

1. On the understanding that both parties are interested in meeting to consider possible collaboration to indentify commercial applications for research undertaken by Tavs Jorgensen, University College Falmouth.
It is agreed that all information, whether oral, written or otherwise, that is supplied in the course or as a result of so meeting shall be treated as confidential by the receiving party.

2. The receiving party undertakes not to use the information for any purpose, other than for the purpose of considering the said collaboration, without obtaining the written agreement of the disclosing party.

3. This Agreement applies to both technical and commercial information communicated by either party.

4. This Agreement does not apply to any information in the public domain or which the receiving party can show was either already lawfully in their possession prior to its disclosure by the other party or acquired without the involvement, either directly or indirectly, of the disclosing party.

5. Either party to this Agreement shall on request from the other return any documents or items connected with the disclosure and shall not retain any unauthorized copies or likenesses.

6. This Agreement, or the supply of information referred to in paragraph 1, does not create any license, title or interest in respect of any Intellectual Property Rights of the disclosing party.

7. After 5 years from the date hereof each party shall be relieved of all obligations under this Agreement.

Signed

For University College Falmouth
Date

Signed
Date