A 4D PRINTING COMMUNICATION FRAMEWORK FOR DESIGNERS AND ENGINEERS

A Thesis Submitted for the Degree of Doctor of Philosophy

by

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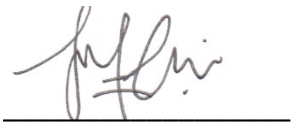
DECLARATION OF AUTHORSHIP

I declare that this thesis is my original work and was conducted in accordance with the Code of Practice for Research Degrees, and was written by myself, except where otherwise stated. This research work has not previously been accepted for any degree and is not being concurrently submitted for any other degree.



Faten Ezrin Azhar

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ABSTRACT

“Communication is an essential part of any design process.”

(Clarkson and Eckert) [1].

The rapid emergence and growth of 4D printing technology are expected to impact the technology's development significantly. Due to the high level of interest shown by the research and manufacturing sectors, the technology is expected to jump in its development rapidly. Since 4D Printing technology is still in the early stage, it is also required to focus on advancements in the progress of emerging needs for development in various areas such as application, design, materials, etc. This thesis investigates the communication barriers between designers and engineers in communicating the 4D Printing design process, which has revealed there are only ambiguous ways of communicating without standardization, which led to misinterpretation in the communication of the 4D Printing design process. This thesis aims to develop a concept of design representations that can be used to communicate the 4D Printing design process. The study proposed a communication framework for a communication tool to aid the communication barriers between designers and engineers in the 4D Printing design process to optimize the effectiveness of the 4D Printing technology through the design process. The 4D Printing communication framework has been developed from idea generation through a series of iterative stages to bridge the communication gaps. The communication framework aimed to guide how to constructively design representation symbols for effectively communicating in the 4D Printing design process. With the standardization of communication tools, the designer and engineer could fluently refine and connect their approach design ideas and maximize the potential of 4D Printing technology.

Keywords: 4D Printing, communication, symbol, additive manufacturing, toolkit.

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LIST OF ABBREVIATIONS

Acrylonitrile Butadiene Styrene (ABS)

ABS material is used by various manufacturing industries for parts requiring structural integrity and detail and is ideal for "wear and tear" projects. It is commonly used in rapid prototyping and additive manufacturing environments to test impact and durability.

Additive Manufacturing (AM)

Unlike subtractive manufacturing, which involves cutting away at a solid block to create an object, additive manufacturing is not performed in this manner. Instead, it involves building an object by building it layer by layer.

British Standards Institution (BSI)

The British Standards Institution is the national standards body of the United Kingdom. BSI produces technical standards, and its codes of practice and specifications cover management and technical subjects ranging from business continuity management to quality requirements.

Computer-Aided Design (CAD)

Computer-aided design (CAD) software is commonly used in various industries and occupations to create drawings and documents, such as building plans, architectural designs, and mechanical drawings.

Four-Dimensional Printing (4DP)

Through 4D printing, an object can be transformed into another structure after being 3D printed. This process can be performed through external energy sources such as light, temperature, and environmental stimuli.

Poly Lactic Acid (PLA)

PLA material is a thermoplastic polymer made strictly from renewable resources. Poly Lactic Acid (PLA) is generated from a biodegradable material like cornstarch, potato starch, sugarcane and tapioca roots and has a smooth, shiny appearance.

Potential Hydrogen (pH)

The pH level is a measure of potential hydrogen in water-soluble substances. It is represented on a scale of 1-14, with numbers representing neutral points and acidity. Values below 7 indicate the substance is acidic, while values above 7 indicate it is alkalized.

Shape-Memory Polymer (SMP)

One of the most commonly used materials in 4D printing is the shape memory polymer, which can fix a temporarily deformed part. It can also be used to return the part to its original shape after being subjected to various external stimuli such as light, temperature, and humidity.

Standard Tessellation Language (STL)

The STL file format is a native component of the 3D Systems' stereolithography software. It can create various drawings and documents, such as building plans, architectural designs, and mechanical drawings. Also, they are widely used in 3D printing and rapid prototyping.

Technical Product Realization (TPR)

The term product realization refers to the various processes that are involved in the development and production of a product. It covers the various stages of a product's life cycle, from conception to completion.

Temperature (Tr)

A thermometer is used to measure the temperature, and these are typically calibrated using different reference points and substances. Some of the most common temperature scales are Celsius, Fahrenheit, and Celsius, respectively, used for scientific purposes and are the primary reference standard for the International System of Units. The other two are the Fahrenheit scale and the Kelvin scale, mainly used for scientific purposes.

Three-Dimensional Printing (3DP)

3D printing, also referred to as additive manufacturing, is a process that involves making three-dimensional solid objects out of a digital file. The materials are laid down continuously in an additive process to create an object.

Ultraviolet (UV)

Ultraviolet radiation is energy produced by the sun and some artificial sources, such as arc welders and solariums.

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1.1 Research Introduction

3D Printing or Additive Manufacturing is a manufacturing process that involves layering materials to create a three-dimensional object [2]. In recent years, 4D Printing has gained considerable interest and is known as the future of 3D Printing [3]. 4D Printing enables dynamic 3D structures or shapes to easily change the shape of the static 3D Printed objects [4]. Through the process of 4D printing, a 3D-printed object can transform into another structure due to the influence of external factors such as light, temperature, and environmental stimuli. Unlike traditional 3D printing, this process does not alter the object's shape after it has been made. This new technology will undoubtedly benefit many industries by using this innovative technology and potentially change everything from daily life to the future of the global economy with significant advancements [5]. In addition, 4D Printing technologies have been recognised as a digital manufacturing process where 4D Printed parts can change their shape over time [6]. Moreover, researchers are currently making 4D objects of larger sizes and developing specific materials for a 4D Printed technique that can respond to water, heat and light conditions [7]. New interactive technologies can pose challenges, such as technological issues and communication barriers. To overcome these challenges, designers often use sketches or hand-drawn images as communication tools in the early stages of the design process. However, it is crucial to carefully consider the medium for communication, as poor representations may cause confusion and errors. By solving the communication barrier, designers and engineers can communicate and conduct 4D Printing with new and existing design manufacturing in an integrated and easy way. There is a continuous need to re-look at the research questions and data sources and refine them after verifications from new findings. The overall aim of this research is to understand how designers and engineers communicate to make full communication of 4D Printing, such as to transform an object so that the specific object could need more investigation into other forms of shape changes. The research will attempt to structure and standardize the communication of 4D Printing to communicate with product designers and manufacturing engineers. By conducting a framework of a design process, designers and engineers will complement each other and enhance the predictive performance of 4D Printing systems. Thus, maximising the potential of this new technology.

1.2 Aims of Research

To investigate how designers and engineers can effectively communicate in the 4D Printing design process. The aim of this research is to explore effective communication strategies for designers and engineers involved in the 4D Printing design process. To achieve this goal, the study proposes the development of a communication tool that can aid in the communication of 4D Printing parts design. The research suggests that the development of a communication framework is necessary to provide guidelines for effective communication during the 4D Printing design process.Based on the aim of the research, the objectives have been identified, and the following research questions are set as guidelines to fulfil the research objectives:

1.3 Research Objectives

1. To examine and classify the communication barriers between designers and engineers when designing 4D Printed parts.
2. To investigate types of representations between designers and engineers when designing 4D Printed parts.
3. To develop a framework to enhance communication between designers and engineers when designing 4D Printed parts.

1.4 Research Questions

1. What are the existing barriers between designers and engineers when communicating about 4D Printing?
2. What type of design representation is the most effective in communicating aspects of 4D Printing?
3. How can the communication of 4D Printing between designers and engineers be improved?

Table 1. Stages of answering research questions for this research.

Research Questions	Research Objectives	Methodology
1. What are the existing barriers between designers and engineers when communicating about 4D Printing?	To examine and classify the communication barriers between designers and engineers when designing 4D Printed parts.	Literature review Expert interviews Focus Groups
2. What type of design representation is the most effective in communicating aspects of 4D Printing?	To investigate types of representations between designers and engineers when designing 4D Printed parts.	Focus Groups Survey
3. How can the communication of 4D Printing between designers and engineers be improved?	To develop a framework to enhance communication between designers and engineers when designing 4D Printed parts.	Data Collection Survey Outcome

1.5 Research Contributions

The study has made contributions to the knowledge in the field of this PhD research as below:

This thesis makes four main contributions. The first is the investigation of the communication barriers that arise during the 4D Printing design process. Through a literature review, this research identified communication barriers between designers and engineers. Specifically, the review highlighted the ambiguous ways of communicating the 4D Printing process, as discussed in Chapter 2, Section 2.6.1.

The second contribution of this thesis is the development of a communication framework based on the research methodology. This research has proposed a conceptual framework to aid communication between engineers and designers in the 4D Printing design process. The conceptual framework was developed from the findings of empirical design research, and the results can be a guideline by other researchers for further investigation. It provided the information that will be helpful to assist future researchers as a guideline in choosing a feasible 4D Printing communication tool design that meets their needs. This contribution is relevant to academic researchers as it provides guidelines for future research on the methodology of the conceptual framework theories of acquiring symbols needed for communication tools.

The third contribution of this research is the proposal of a set of graphical symbols as a communication tool for the 4D Printing design process underpinned by a conceptual framework as the solution for the communication barriers. Currently, no previous study has empirically explored the effects of communication on communication framework and design representation in an academic setting. Related research has shown that graphical symbols can ease the design process (see Caffaro,2018 and Karal, 2016) [8] [9], which proves the necessity of the research done in this thesis. As far as the theoretical contributions of this study are concerned, the study contributes to the understanding of some related constructs that have not been explored in-depth in any literature relating to 4D Printing technologies. This research helps standardise the communication system and insists that designers and engineers communicate effectively in designing 4D Printing products.

The fourth contribution to these studies is the proposed communication toolkit prototype on the web. The concept of the communication toolkit and the symbols of correlated 4D Printing elements contribute to design research. The proposed toolkit prototype design contributes to the software development as the toolkit aims to be applied as CAD Software in the future. Although the study is focused on providing a comprehensive understanding of the various elements of a communication process, further research is needed to improve the design.

1.6 The Structure of the Thesis

This thesis consists of seven chapters, the arrangement of this thesis is divided into three research phases. **Phase 1:** introduction and investigations, **Phase 2**: research methodology and **Phase 3**: data collection, idea generation, development and evaluation. The following order presents the relation between each phase with its related chapters, followed by the summaries of each chapter.

Phase 1: Introduction and Investigations

Chapter 2 Literature Review

This chapter justifies the research problem statements by providing the current known knowledge and the theory behind the research study goal. The literature review aims to provide a chronological sequence of what already exists and show the current state of the art.

Phase 2: Methodology

Chapter 3 Research Methodology

This chapter discusses and justifies the research philosophy, the methodology used to conduct this research, and the issues related to the chosen research methodology. The survey sample group, data collection methods, stages of collecting the data from the field, the procedures and problems encountered during each fieldwork stage, the actual data collected, and the analysis methods are described in the chapter.

Phase 3: Data collection, Idea generation, development, and evaluation

Chapter 4: Data Collection (Primary research)

This chapter describes the primary research for data collection used in this study, such as interviews and focus groups, to test the research objective and answer the research questions. This chapter presents the conducted data collection process and the actual data recordings. Then this chapter organised the information and conducted the data analysis process. The sampling method is presented to select participants in the primary research. Also, the tools, procedures and materials are described for data gathering observations without intervening.

Chapter 5 Development of 4D Printing Communication Design Representation

This chapter discusses the development and testing process of the 4D Printing communication toolkit. It presents the symbol development with respect of results obtained in interviews and focus groups in Chapter 4. The outline of the testing process was implemented to gain a response from the participants in two custom made online surveys. Overall, stages of development of the toolkit are described, followed by improvement of the design representation from each stage. The chapter concludes with the final set of symbols.

Chapter 6 Development of the 4D Printing Communication Framework

The chapter presents the proposed conceptual framework for the 4D Printing communication toolkit. The innovation of the conceptual framework is to support communication accuracy by focusing on the elements of communicating 4D Printing parts. The implemented communication toolkit uses the final set of the symbols from Chapter 5.

Chapter 7 Conclusion and future work

The insight of this chapter is to present research findings, what the research has offered that is important to the research study, the sample population, and the general body of knowledge. The chapter concludes the thesis by re-addressing the limitations of the study and answering the research questions, providing suggestions for future work.

1.7 Research framework of the thesis

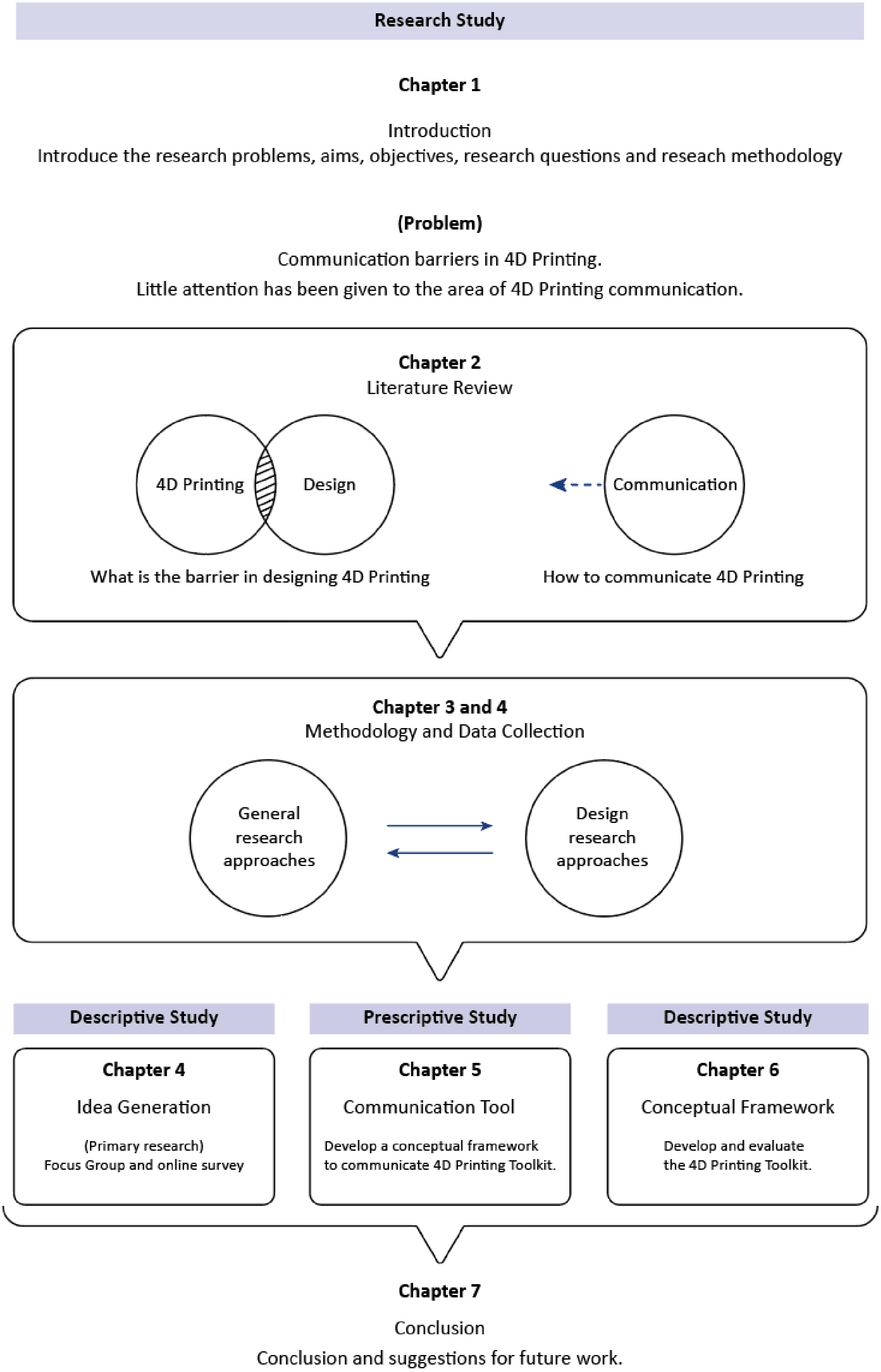


Figure 1. The research framework of this research.

Figure 1 illustrates the research framework that provides the orientation to the study of this thesis. Chapter 1 draws the outlines of the introduction of the research topic, the problem statement, the aim, and the objectives and questions of this research study. Chapters 2 provide literature reviews about communication, information processing, and how cognitive communication can be processed in applying 4D printing products. Also, Chapter 2 reviews the features of 4D Printing, which involve definitions of communication and 4D Printing technology and recent studies regarding the design process. Then, Chapter 2 describes how communication processes information and how designers and engineers perceive it. Chapter 3 explores general research approaches and design research approaches. Chapter 4 describes the data collection of interviews and focus groups. Next, Chapter 5 presents the development of the design representation for the 4D Printing design symbols. Finally, Chapter 6 presents the development of a conceptual framework. Also, the chapter presents implemented the 4D Printing communications toolkit to evaluate the conceptual framework.

1.8 Chapter Summary

No studies on the communication aspects of 4D Printing are currently embedded in the literature, especially in the design process. This study aims to find whether an ideal standard for communicating the 4D Printing design process exists. The study raises three research questions on overcoming the communication barrier between designers and engineers in 4D Printing in the design process. The study aims to conduct empirical research to examine the communication barriers between designers and engineers through communication design activities. It is intended to structure and standardise the communication between designers and engineers in order to communicate 4D Printing.

Following the literature review, the research attempts to establish the communication between designers and engineers in the 4D Printing design process. The standardisation of the communication tool is seen as potentially to reduced the barriers field and the research gaps. Then to address the research gaps study will conduct research of semi-structured interviews and research iterations. The research results will be a foundation for the new conceptual communications framework for 4D Printing design process.

Chapter 2:

LITERATURE REVIEW

Chapter 2

LITERATURE REVIEW

Chapter content

Chapter Two provides a review of relevant literature relating to the research topic. It is intended to highlight the multidisciplinary nature of the development activity and provide background information on the research area of the thesis. This chapter provides a literature review that should be considered by a collection of empirical research, analysis of the barriers and existing research relevant to 4D Printing, communication, engineers and designers. Throughout the chapter two summary, the researcher addressed the gap in the thesis.

2.1 Introduction of 3D Printing

Three-dimension Printing (3D Printing), also part of a process known as additive manufacturing (AM), is an evolution from traditional manufacturing methods [10]. 3D Printing is one type of manufacturing that involves making an object by adding material one tiny layer at a time [11]. Moreover, 3D Printing allows designers and engineers to create complex parts for machines, aeroplanes and cars at a fraction of the cost and time of standard, which means processes like forging, moulding and sculpting [12]. Due to the complexity of 3D Printing, traditional manufacturing techniques are often used to analyze the parts created through this process. They can provide a deeper understanding of the various constraints that must be resolved to create effective and efficient products [13].

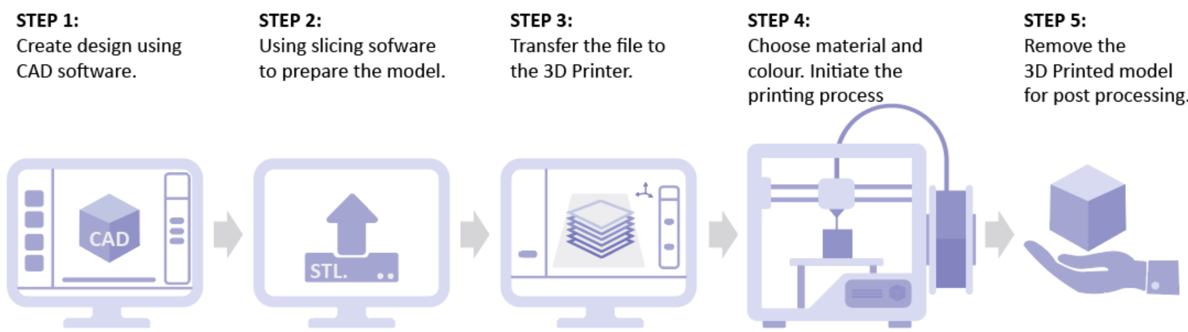


Figure 2. Illustration of the Additive Manufacturing processes.

This emerging technology process of additive manufacturing mainly consists of five primary stages; the first step in 3D Printing is (Modeling) by creating a blueprint that the object designer or engineer wants to print. The 3D Printing process begins by creating a digital design of the object using CAD modelling software, which is often referred to as 3D Printing software. There are several software programs available for creating digital models, including Blender, SolidWorks, and Fusion360. [14]. The next stage is called *Slicing*, and the 3D file will then transfer and send an instruction to a 3D Printing slicing software. Several slicing software to build preparation software and 3D Printer hosts such as Cura, Netfabb or Simplify3D scan the files and slice it into sections to help the printer understand the shape and print the model with the estimated print material and time [15]. Once all the parameters are set, the next step is 'Printing', where the part is built by adding layer after layer using a particular type of raw material, for example, filament, resin, plastic, metal, etc., through the different types of

3D Printer machine [16]. After building the part and potentially applying the cooling and curing process, the model can be removed from the 3D machine. Figure 2 shows an example of how the additive manufacturing process works. The object is created through the layer by layer process in an extrusion-based 3D Printer (Material Extrusion) as it is the most well-known type of 3D Printing.

The advantages of 3D Printing innovation include low cost, in which every item can be customised geometry object to meet users' specific needs without impacting the manufacturing costs [17]. 3D Printing can contribute to waste reduction, generating less waste compared to other conventional manufacturing methods [18]. Furthermore, the flexibility of different materials can be used in 3D models, making it very easy to create construction models and prototypes for a wide variety of projects within many industries [19]. Another 3D Printing advantage is quality assurance, where the technology builds robust products with superior functionality [20]. The major of this process is that it works directly from a computer model software, which allows users to devise entirely new shapes without regard for existing manufacturing limitations.

2.1.1 Type of 3D Printing Techniques

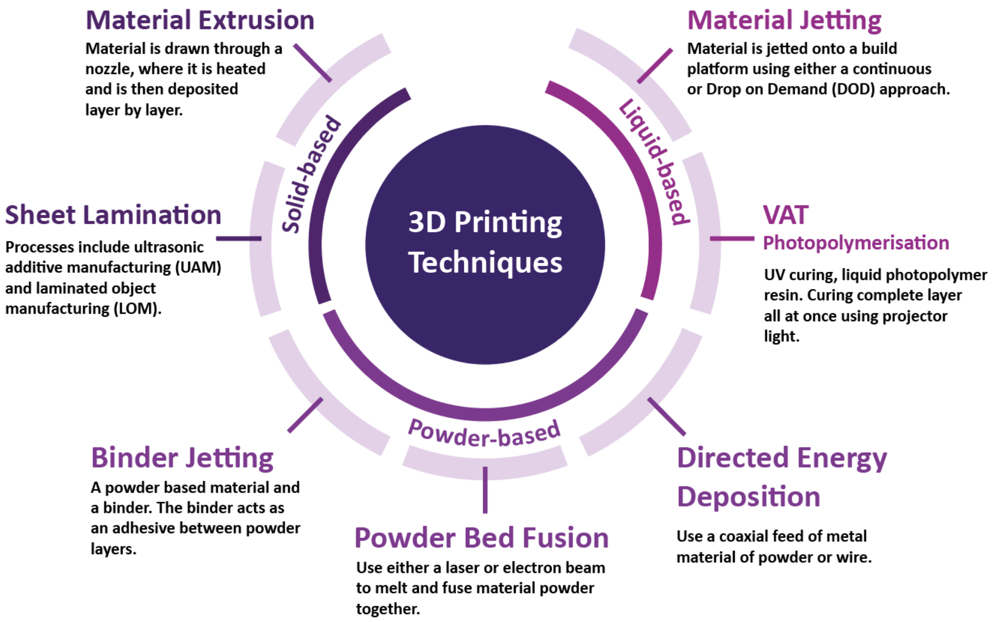


Figure 3. The seven categories of Additive Manufacturing techniques into solid, liquid and powder feed

3D printing processes can be categorized into three main types: solid-based, powder-based, and liquid-based techniques. Each technique has its unique strengths and applications [21]. Solid-based techniques include Material Extrusion (ME) and Sheet Lamination (SL). ME is common in industrial additive manufacturing, using thermoplastics like ABS and PLA. SL or Laminated Object Manufacturing (LOM) involves bonding sheets of material to create objects, and can be used with a variety of metals and ceramic-metal combinations [22]. Powder-based techniques consist of Binder Jetting (BJ) and Powder Bed Fusion (PBF). BJ uses a liquid binder to selectively deposit on a powder bed, creating metallic, ceramic, and sand parts [23]. PBF, including SLS 3D printing, uses an energy source to fuse powdered material, allowing for the creation of complex geometries. Directed Energy Deposition (DED) is a similar process, using powerful lasers to melt and solidify metal powder or welding wire materials.

Liquid-based techniques, such as VAT Photopolymerisation (VP) and Material Jetting (MJ), use resins and photopolymers that react to UV light. VP utilizes a resin tank and an LCD screen to create patterns, while MJ employs an inject-style printer head to jet photopolymer directly onto a build platform. These techniques are capable of producing multi-material 3D printed parts and assemblies in a single step [24]. The choice of technique depends on factors like part size, geometry, and the desired material properties. Advancements in 3D printing technology have fueled the development of novel applications in biotechnology and other industries, leading to the emergence of 4D printing, which aims to overcome the limitations of traditional 3D printing.

2.2 Introduction of 4D Printing

Additive manufacturing innovative technology for the future manufacturing process of making 3D solid objects from a digital file is changing how manufacturers everywhere think about design, prototyping and production [25]. However, the development of smart-materials or intelligent materials has provided a revolutionary process in the field of 3D Printing, which is termed four-dimensional Printing, also called (4D Printing) or (4DP) [26]. 4D Printing technology refers to a 3D Printing object with a 3D Printer. Still, after printing, the object can transform from one shape to another based on the external conditions the object gets exposed to stimuli [6]. Moreover, those external conditions include heat, water light, magnetic field, mechanical force or other types of energy [27]. The fourth dimension is the ability to change shape and form over time to create an object that is no longer static using smart-materials. The objects can shift or reshape and progress, accompanied by the function involved in the process [28]. Figure 4 shows an example of the elements and the categories involved in 4D Printing.

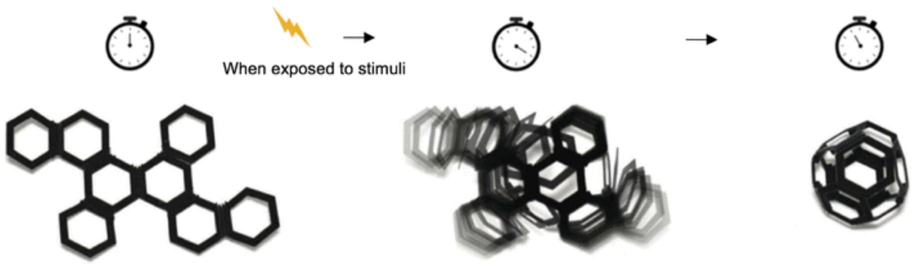


Figure 4. 4D Printed "transformation over time" from a flat structure to a truncated octahedron.

Since 4D Printing technology is still in the early stage, it is also required to focus on advancements in the progress of emerging the area of smart-materials, which is also at an infancy stage as well [27]. On the other hand, 4D Printing has the potential for transforming advances in biotechnology, medicine, tissue engineering, and chemotherapy. Additionally, self-assembling biomaterials medical devices such as stents and splints, orthodontic devices and implants that can grow with the patient are some of the advances that come from 4D Printing technology [26]. As a result, many organisations are investing heavily in developing 4D Printing. For Example, Massachusetts Institute of Technology (MIT), Stratasys, one of the leading global 3D printing manufacturers, and Autodesk, a leading 3D software developer [29]. Moreover, many other universities and research centres are working specifically in developing 4D Printing or working in the broader context of developing smart- materials [28]. Furthermore, the possible applications for 4D Printing are wide open to imagination. It will also theoretically enable the user to build complex structures that can shift according to its environment or what it is exposed to [30].

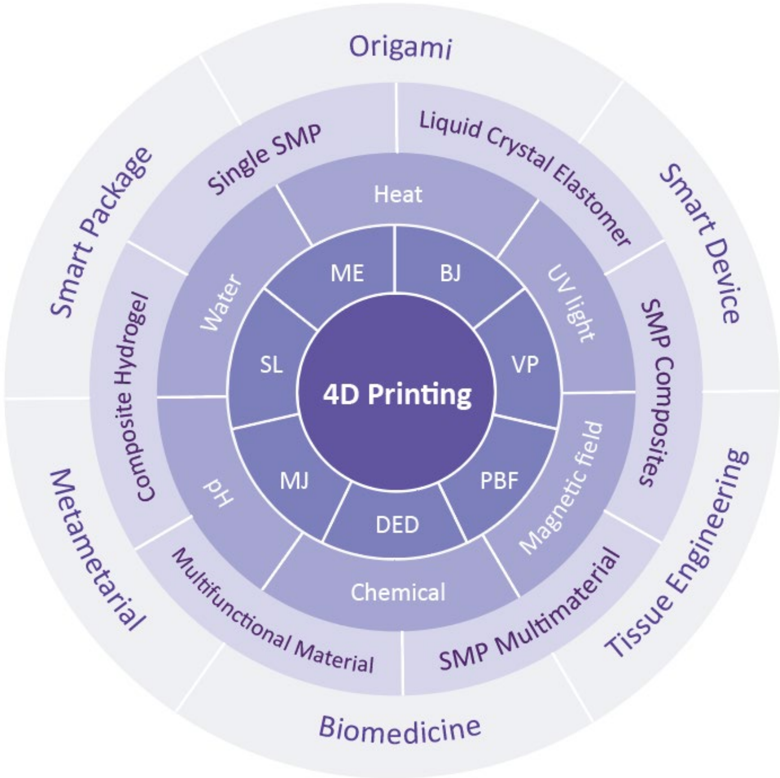


Figure 5. Illustration of the elements and the categories involved in 4D Printing.

Recent significant progress in 4D Printing is reviewed in overcoming these challenges, including Shape-Memory Materials (SMM), which can change shape over time, creating a wide-ranging universe of potential new products with a timed response and external stimuli [31]. In addition, Shape-Memory materials (SSM) could be notably used for small implantable medical devices. Tiny soft devices could be inserted or implanted in people and hardened when they reach the affected area. Still, with a few possible exceptions, the wide-scale application remains years away [32]. Most of the activity is still in research and development, and the market is in its infancy.

2.3 Concept of 4D Printing Process

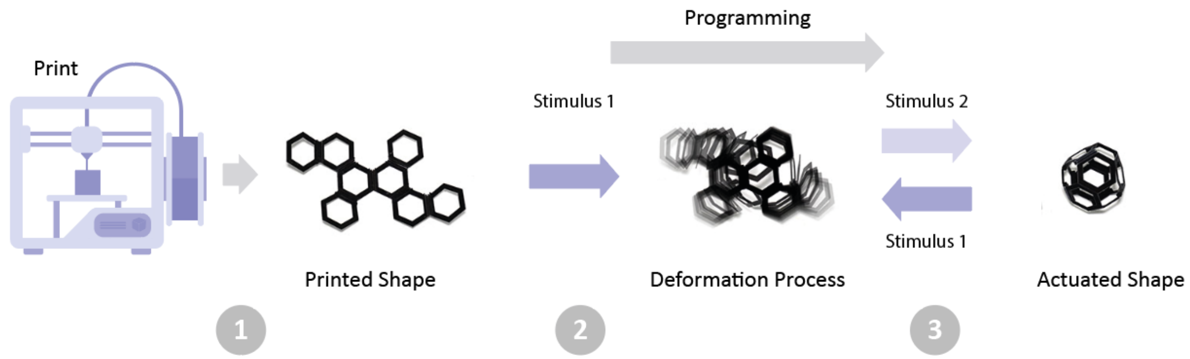


Figure 6. 4D Printing Process (Illustrated by Author -Ezrin Azhar)

In recent years, 3D Printing technology has driven significant innovation in many areas such as design, engineering, manufacturing and others [33]. This response to the change of designer's and engineers' perspectives in designing the object [34]. In order to achieve the creativity possible with 4D printing techniques through the smart-materials and new geometries, creating a computational design method will further assist in assessing the problem that typically involves designing part communication between designer and engineer in 4D Printing [35]. For decades, scientists have been working on materials that can change shape, whether bending, contracting, or wiggling. These kinds of smart-materials could be helpful in robotics, engineering, design, and medicine [36]. However, all of these materials transform relatively slowly, and they need to be connected to a controller with wire and tube or have a limited range of movements and size. Despite that, scientists have developed a flexible smart-material that is remotely activated and can move in multiple ways. In addition, it can transform quickly and change its shape completely in less than a second; this material also can be 3D printed [37].

As mentioned, the capabilities of 4D Printing are to respond to the environment over time. The process of 3D printing objects is described in detail. In order to create the object, computer-aided design and mathematics are used to implement the print path instructions. Compared to the 3D Printing rigid object, 4D Printing is characterised by the ability to shape-shift the printed object behaviours [38]. Moreover, the shape-shifting behaviours in 4D printed objects produced by the different external stimuli cause programmed shrinkage, expansion or folding of the printed objects [39]. 4D Printing object is transformed into its size through computational format generated by the Computer-Aided Design (CAD) program as an end product of the 3D modelling process [40].

However, the main difference between 3D and 4D Printing depends on the shape-shifting material (SSM), which is the advanced material that indicates specific changes in response to external conditions [41]. Furthermore, SSM is termed as such due to its shape change behaviour, defined as the form and/or sizes capable of reversibility in response to specific external stimuli [42]. The potential of 4D printing technology to create new structures has been greatly expanded by its ability to expose them to various triggers, such as heat and light. Through the use of manufactured components, small changes can create new and completely different structures.

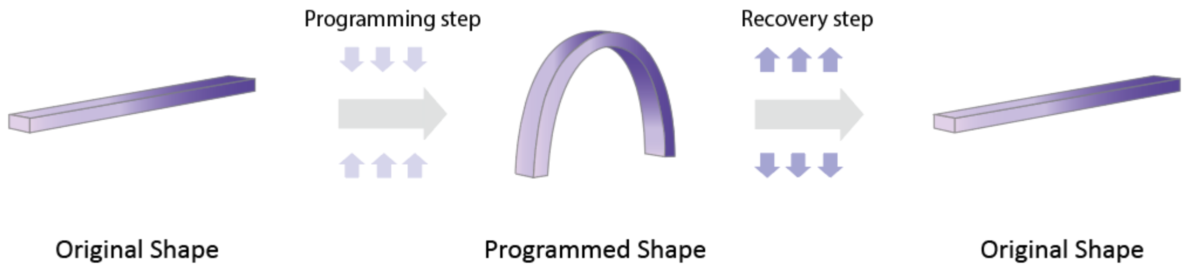


Figure 7. Illustration of Shape-Memory Effects (SMEs) one-way process.

The shape-memory effect (SMEs) can be retained and converted back to the original shape with appropriate stimuli-responsive materials. The SMEs are usually described by the shape-memory cycle (SMC) as shown in Figure 7., the transformation through how this stimulus phenomenon is achieved by using the programming stimuli in 4D Printing [43]. The concept of the accumulated strain energy is discovered in the process of processing material. This energy can then be used to detect a functional change. SMEs can be one-way, two-way, three-way, or multiple-way [44].

2.3.1 Type of shape-changing behaviour

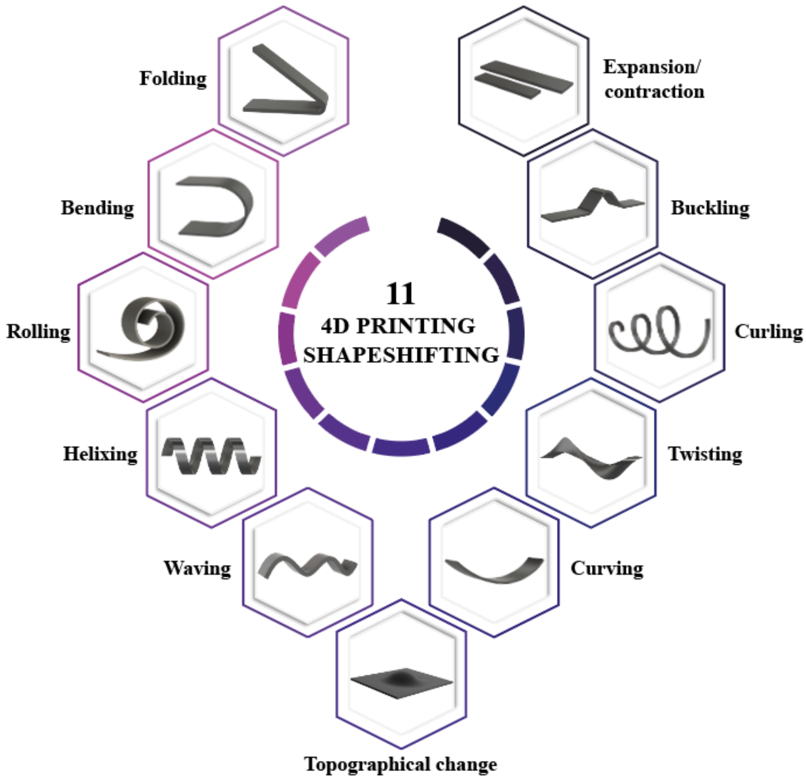
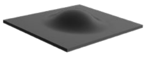
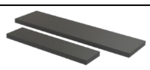


Figure 8. The 11 shape-changing behaviours of 4D Printing, influenced by Nam,2019 [40] (Illustrated by Author: Ezrin Azhar)

Currently, shape memory polymers are used in various research projects to create 4D printed components. These materials can return a part's original shape after it has been deformed [45]. Furthermore, another helpful taxonomy of 4D Printing shape change behaviours concepts was provided by (Nam, 2019). The study thoroughly reviewed the shape change behaviours literature and identified three categories: basic shape change, complex shape change, and a combination of shape-change [40]. This research study focused on eleven shape change behaviours, including folding, bending, rolling, helixing, twisting, waving, curling, curving, topographical change, buckling and expansion. According to Nam and Pei (ibid), a fold is a sharp curvature caused by deformation along a crease. As shown in Figure 8, it is different from a bend, a more evenly distributed deformation of material along the deflected area that creates the curvature. Rolling is different behaviour in which the shape moves by turning over and over on its axis.

Table 2. Taxonomy of 4D Printing shape changes behaviours, adapted from (Nam,2019) [40]

Shape-change behaviour	Description of Behaviour
	A **fold** is a sharp curvature caused by deformation along a crease.
	**Bending** is the distributed deformation of material along the deflected area that creates the curvature
	**Rolling** is a behaviour in which the shape moves by turning over and over on its axis.
	A **helix** is a type of smooth space deformation in which a curve occurs in a three-dimensional space.
	The **waving** behaviour results in a shape that has undulating features or a wavy up-and-down form.
	**Curling** As an alternative to curved creases, can use surface curling by creating continuous surfaces.
	The **twisting** action is dominated by in-plane stretching.
	**Curving** is the amount by which the surface of a geometric object deviates from a flat plane.
	The **topographical change** results in a distorted shape that resembles the physical features of a ground terrain.
	**Buckling** is characterised by a sudden sideways failure of a structural member subjected to high compressive stress.
	**Expansion** and **contraction** shape-changing behaviours are based on a shape-memory cycle.

On the other hand, twisting is dominated by in-plane stretching. A helix is a type of smooth deformation in which a curve occurs in a three-dimensional space. Buckling is characterised by a sudden sideways failure of a structural member subjected to high compressive stress or force. Curving is the amount by which the surface of a geometric object deviates from a flat plane. Topographical change results in a distorted shape that resembles the physical features of a ground terrain. Expansion and contraction shape changing behaviours are based on a shape-memory cycle. The waving behaviour results in a shape that has undulating features or a wavy up-and-down form. Lastly, curling produces a similar effect as curved creases along a continuous surface. There are also notable differences in the degree of shape-changing (Nam and Pei, 2019) [40]. Curving, twisting and helixing shape change behaviours have deformation angles occurring in the hinge area while bending, topographical and twisting shape-shift behaviours have a deformation that results in less than 360°. If this is more than 360°, the deformation is classed as rolling, buckling or curling.

4D Printing shape-changing behaviours used advanced material called shape-memory materials (SMMs), a class of polymeric materials that can be programmed to memorise a predetermined configuration. SMMs revert the material or structure when subjected to an external agent or a specific temperature [46]. The ability to self-assemble, which in the long run, can reduce the workforce needed in factory lines. In addition, the user will be able to design industrial and home equipment like pipes with embedded safety features in their opening and closing in response to how hot the environment temperature is or in response to other factors. For example, having a sports shoe that will adapt and behave differently according to the conditions of the environment they are in or according to the conditions of the person wearing them. 4D Printing also will be able to design medical implants that can continuously transform inside the person or more intelligent medical equipment that can support different medical procedures. Those are some of the applications many researchers look forward to with 4D Printing technology to control different shape-changes materials.

2.3.2 Stimuli-Responsive and the shape-memory effect (SME)

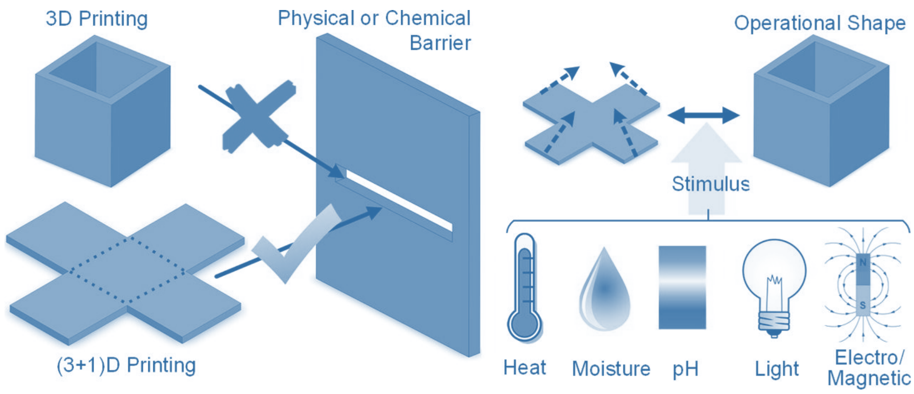


Figure 9. Smart-materials are responsive to external stimuli [47].

4D Printing is an emerging technology for fabricating complex, stimuli-responsive 3D structures, providing great potential in many applications, which has the ability to be deformed and held into a temporary shape or form [48]. A stimulus is something that elicits a response by design and material. The typical external stimuli causing the transformation in the properties of the materials used in 4D Printing are heat, water, light, pH (potential of hydrogen), magnetic field and others [49]. Figure 10. Shows the example of how the stimuli-responsive to the UV light. Moreover, 4D Printing is able to return to and remember its original shape with a specific activation program, which is required shape-memory polymer (SMPs) and shape-memory alloys (SMAs) [50].

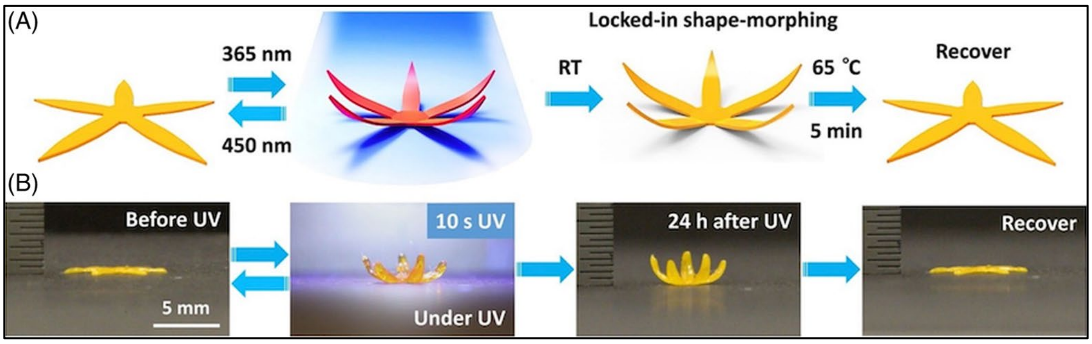


Figure 10. The example of shape-changing behaviour [51].

SMAs are known as an alloy that can be deformed when cold and heated up; they will return to their pre-deformed shape. The SMAs memory alloy has two stable phases, which is (1) the high-temperature phase called 'austenite' and (2) the low-temperature phase called 'martensite'. These effects of change and return transformation with martensite and austenite are called shape-memory effects (SMEs) [52]. Thermoresponsive shape memory polymers (SMPs) based on poly(ε-caprolactone) (PCL) is a polymer that can shift its shape and/or apply a force in response to a stimulus [53]. On the other hand, the temperature is the primary stimuli as the transition temperature (T trans) at which SMPs the class of stimuli-responsive materials triggered. However, it is not a material property but an effect caused by the proper programming of the material that has to appropriate polymer structure [54].

2.3.3 Stimuli and Potential Applications of 4D Printing

The term 4D printing refers to a process of technology that allows a device or an object to be transformed into a pre-programmed 3D form using a single or multi-material material. This process can also create different types of objects [55]. There are various types of stimuli that can be categorized into four categories: physical, biological, chemical, and combinations of these. This section discussed the interaction between these stimuli and their responsive materials. The usage of 4D Printing applications will also be discussed, followed by the need to be considered in the future. Understanding the external stimuli that can affect the properties of 4D printed materials is very important to develop effective and efficient materials. This knowledge can help to design and implement an external response to the stimuli. These include light, water-humidity, magnetic field, temperature, and pH.

Despite the technological advancements that have occurred in the 4D printing industry, it is still in its early stages when it comes to developing new products. Various uses for 4D printing have applications in biomedical sciences to soft robotics, from self-healing products to active origami, etc. Several applications demonstrate the potential to transform how new product development is carried out. One of the most promising applications of 4D printing technology is in medical developing soft robotics. A group of researchers from the ARC Centre of Excellence created valves designed from shape-memory materials to respond to water temperature [56]. In addition, the MIT Media Group has developed a novel pasta that can respond to various types of water and heat conditions [57]. The flexible and flat pasta can bend, roll, and fold differently depending on its shape. To achieve this effect, 3D printing a piece of edible gelatin over the top of the pasta.

Aside from medical applications, 4D bioprinting has also been used in various scientific fields, such as tissue engineering and drug delivery. The other advantages of 4D printing include its ability to produce various products to support components for use in automotive parts to human organs. It can also reduce manufacturing costs and carbon emissions by using adaptive materials. In addition, according to a study by market research future [58], it is expected to be widely used in various other industries such as construction, automotive, healthcare, and utilities. Through its various capabilities, 4D bioprinting has the potential to transform the field of tissue engineering and bring organ development one step closer.

Water – humidity responsive

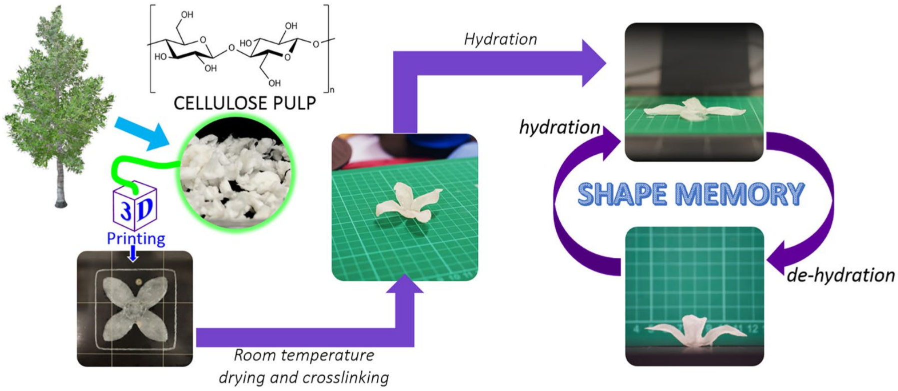


Figure 11. Water-responsive stimuli.

In 4D printing, humidity and water were first used as stimuli. Due to their wide application, materials sensitive to humidity and water are of interest. They can be used to alter the structure's shape underwater, which can be restored after drying. However, the degree to which material contracts or expands during the transition to its final form should be controlled. The design was able to deploy a flat configuration upon hydration. The structure was then able to recover from its previous state through the use of a responsive pulp-hydrogel composite ink [59].

Heating Temperature

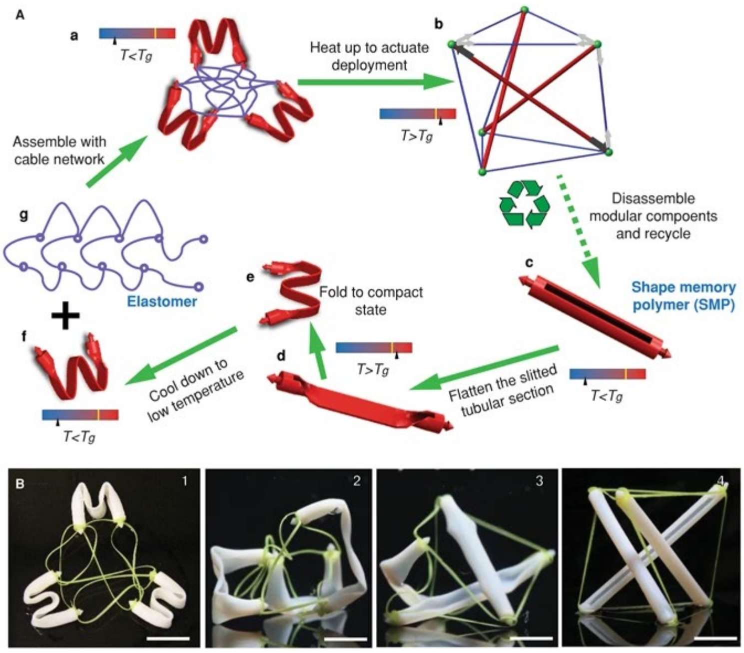


Figure 12. 3D Printed structures of multi-material grippers with multiple SMPs

The ability of a material to form an integral part of a design is known as its ability to change its properties through various mechanical and thermal responses. This process can be controlled by increasing the temperature and connecting the various components of the design to a network of flexible cables. An active tensegrity can be created by implementing a material's shape recovery properties through its shape memory polymers. After heating up, the shape recovery properties of the material can be changed through the activation of the tension structures. These structures can then be used to create a 3D resilient tensegrity. This process aims to create a 3D printed version of the tubular shapes of the SMUPs using a combination of 3D printing and injection processes. These shapes are then folded into compact sizes, assembled using cables, and connected to the SMUPs to form a loose assembly. The tension structures are then subjected to self-stress when the temperature reaches a certain point. The results of the test revealed that the tension structures were able to achieve a stable tensegrity. The scale bars shown in the image represent 15 millimeters. This technology can be widely used in various applications, such as in the bio-medical and soft robotics sectors. It can provide a defined response to the stimulus, which can help develop new and sustainable materials [60].

pH-responsive hydrogel

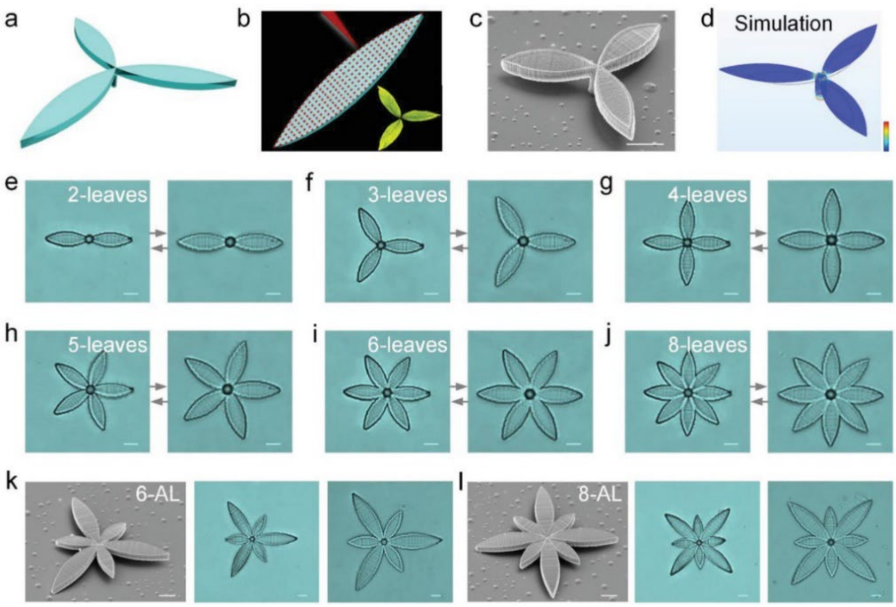


Figure 13. Demonstrates the functioning of pH stimulus in materials which shrinks in acidic solution and swells in the basic environment, thus, utilising their sensitivity in shape actuation [61].

A pH-responsive hydrogel can develop a dynamic behaviour and versatile pH level that can regulate the flow rate under different conditions. The ability of this structure to provide a wide range of stimuli-responsive properties makes it an ideal platform for developing nanostructures and membranes. These hydrogels can exhibit various properties such as temperature, light, ionic changes, etc. The pH refers to the potential of hydrogen concentration in a water-based substance. Figure 13. shows an example of swelling and deswelling of stimuli-responsive biomimetic micro-structures using pH-responsive hydrogel. By imitating the plant leaves in nature (inset of Figure 20b), single-layered blade structures of various shapes are designed and fabricated using the pH-responsive hydrogel. According to the numerical prediction, isotropic swelling occurs once the environment becomes strongly alkaline, consistent with the experimental observation in the above image, ***e***. These processed structures can undergo elegant expansion and contraction when changing the pH values of the liquid environment. The presence of local acidification near the inflammation sites and the pH difference between the gastrointestinal tract and cancer cells have led to the development of pH-responsive materials that can be used to deliver drugs to the targeted organs [62].

UV Light

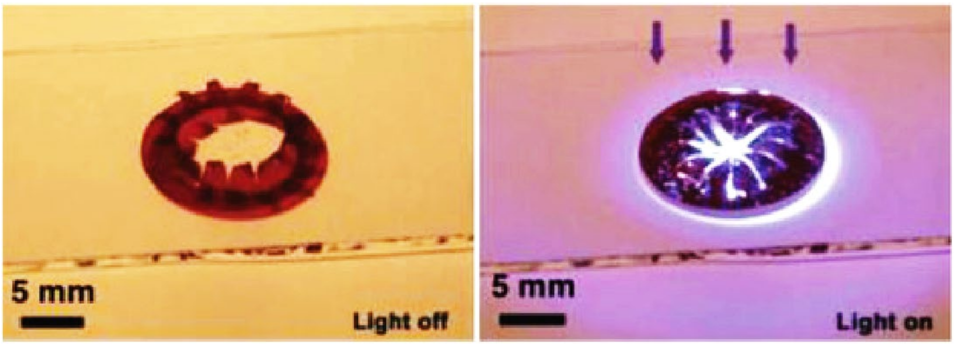


Figure 14. The polymerised film is cut out in a circle with 12 petal-like internal segments. The iris is opened and closed upon UV irradiation without UV light.

Due to the various advantages of light as a stimulus, it has been widely used in recent research to develop new and sustainable materials. Several transitions can be induced by light exposure, such as the formation of photopolymerisation or changes in the shape or size of the stimulus [63]. Photopolymerisation or Stereolithography (SLA) are the processes that activate when a laser beam or ultraviolet (UV) light falls on it. In addition, intermolecular structure changes when UV light is directed across the resin's surface. Then, the light source in the form of a laser will use a scanning system that moves in the x and y direction around the platform or container. Next, when the laser or ultraviolet hits the surface and interacts with the resin, it starts to solidify the particular resin. Figure 14. The polymerised film is cut out in a circle with 12 petal-like internal segments. The iris is opened and closed upon UV irradiation without UV light. Figure 14. shows an example of a light stimulus in 4D Printing using the photopolymerisation process, where once they conceptualise the 3D Printing model, it will then transfer to the additive manufacturing machine. Then, by exposing the UV light in the required area, the platform moves the object down to the z-axis one-layer height until the layering process completes the whole part. This process already sets the particular resolution or thickness in the scanner machine [64].

Magnetic Field

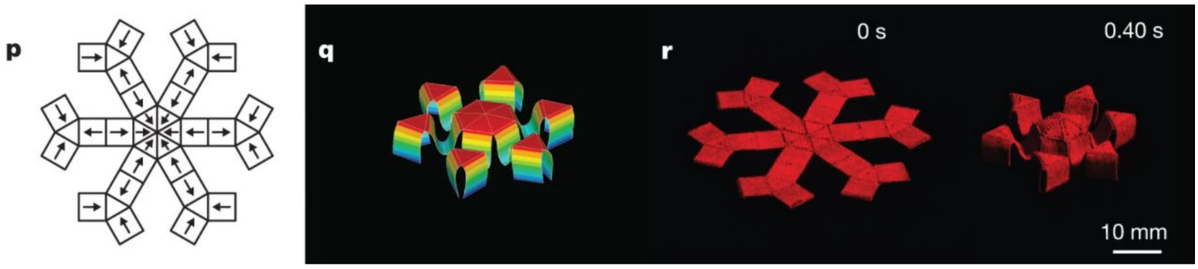


Figure 15. Structures are enabled by folding the magnetically active segments surrounding the magnetically inactive segments.

4D Printed objects can change shape and post-production and are triggered by magnetic fields, and these little shapeshifters can be controlled with the wave of a magnet. The technique uses a soft silicon rubber embedded with tiny iron particles to create the 'programmed' material. A magnetic field magnetises the substance, creating a magnetic material printed into any shape. Moreover, the direction of the magnetic field can be changed during the printing process. The result is a material with a non-uniform polarity, meaning each part of the structure can respond differently to a magnetic charge. The system is so precise that researchers can program a computer model to move in a certain way, such as the shapes can contract, deform, jump and others. As an example, Figure 15. shows how 4D Printing works; two-dimensional planar structures with programmed ferromagnetic domains demonstrate complex shape changes under applied magnetic fields. The elastomeric composite ink contains magnetised particles [65]. These objects are infused with magnetic particles during the print process, and they can be programmed to shrink, fold or even grasp other things. The medical industry would probably benefit from this invention, and this could also lead to controllable microrobots, which can extract tissues or even deliver drugs to specific locations. These tiny magnetically controlled robots also have a fast reaction time and are benign to the human body. For this reason, the challenge is to print the program and coordinate the microrobots. Furthermore, the same movement can be replicated precisely in the physical structure. Because the magnetic field is applied remotely, these materials can be used in small, inaccessible places. Also, the complex shape changes could give soft robots flexible appendages in robotics. In fact, along with the existing smart-materials, this speedy shape-changing technology has numerous potential uses in various industries; it is all with just the flip of the magnetic switch [46].

2.4 Communication

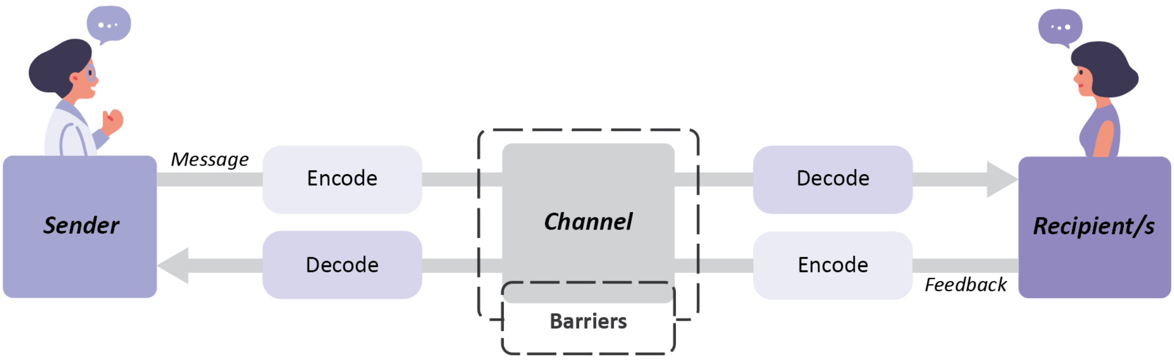


Figure 16. illustration of the communication process.

Communication can be defined as the transmission, interpretation and exchange of information [66]. Typically, the classic example of communication is an eye-to-eye conversation when spoken language was not yet developed. Since we live in a new era and globally connected technologies and high-tech machines are part of our everyday lives, there is more to say about communication, which consists of transmitting, interpreting, and exchanging information. Thus, communication is one of the important parts of 4D Printing design evaluation, as has repeatedly been shown in several studies [67]. By focusing on communication, decision-making in design that is usually subjective will make it much easier to achieve the goal. The fundamental function of the design process is the ability to communicate effectively and send accurate visual messages that others can easily understand. The communication process is highly vital in terms of increasing the effectiveness of communicating. The illustration in Figure 16. above shows the process of communication. There are four components of communication: encoding, decoding, feedback, and transmission medium. A message's sender encodes it and transmits it to the receiver, who then responds by providing feedback [68].

Encoding

The first communication component is the encoding process, which involves translating concepts and ideas into gestures and symbols. The sender must decide whether or not to transmit the message. Failing this process can lead to the loss of good ideas. For instance, if a conversation is muddled with irrelevant facts, it can be hard to have a productive discussion.

Medium or Channel

The second component in communication is sending the encoded message through a channel or medium. Two main types of communication channels are commonly used: oral and written. The former is conducted over the telephone or through Internet-based technologies. On the other hand, written communication is usually done on paper or electronic media. With the use of both verbal and non-verbal cues, oral channels are more effective than written ones.

Decoding

The receiver of a message is responsible for decoding the message that the sender is sending. This process involves analyzing the various elements of the message that the sender is conveying. In order for communication to be successful, the two processes must be in sync. One of the most common factors affecting this process's success is cultural differences.

Feedback

Feedback is the next step in the communication process, and it occurs when the receiver responds to the message. This process can be either verbal or non-verbal, and it can be a combination of these. The sender can take corrective action with feedback, such as retransmitting or rephrasing the message.

> *"Communication…is no secondary phenomenon that can be explained by antecedent psychological, sociological, cultural, or economic factors; communication itself is the primary constitutive social process that explains all of these factors. - p.126."*
>
> *(Craig, R. 1999)*

In 1999, Robert Craig wrote an article in the Communication Theory journal, explaining that communication is constitutive. In other words, communication creates and produces our social world. Moreover, he sees communication as the driving force in our lives and relationships. Communication is exchanging information between the sender, who is sending the message and the receiver, who receives the message [69]. Communication can be verbal, nonverbal, or textual. It can be oral, visual, physical, or any other such method. Although communication occurs in various ways, it is always a learned behaviour. While most humans are born with the physical abilities to speak, hear, see, and so on, people must learn to communicate through codes, standard system symbols or signs, and language systems. This way, communication is a collaborative practice where people use symbols to generate and interpret meaning. In the industrialized cultural sphere, we are today living in mass-media or information societies.

2.4.1 Diagrammatic Theories and Models of Communication

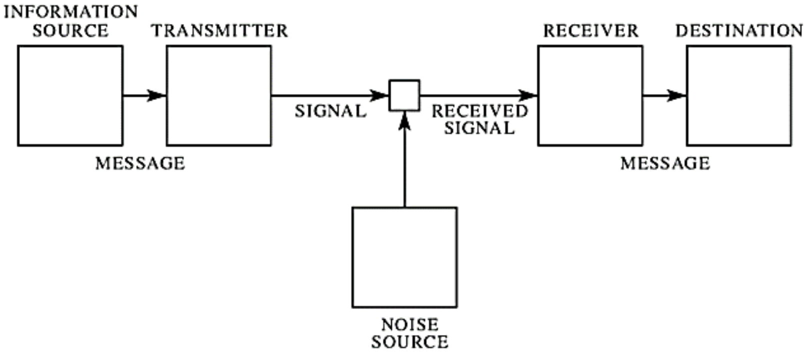


Figure 17. Shannon's and Weaver's schematic diagram of a general communication system [70]

The word communication in Latin comes from *'communicare'* which means to share, to make something common [71]. Years ago in 1949, Claude Shannon and Warren Weaver developed a functional model of communication as shown in Figure 17. In this model, communication happens when the information sources, a sender has a message and transmits that message in the form of a signal through a channel [72]. Then, the signal is received by the receiver at its final destination. Along the way, there might be some noise in the communication system, that could negatively influence the process [70]. However, after several decades and a couple of models to 1962, Dean Barnlund created the transactional model of communication. He then articulated five fundamental principles that reflect the basic components of human communication, which communication is not a thing but is a process. According to Barnlund, communication was not a one-way process, and it had a different nature, a dynamic, continuous and circular. In other words, communication between people is an ongoing, back-and-forth simultaneous exchange. Next, the communication is not linear, but it is circular; they are simultaneously both senders and receivers at the same time. Third, Barnlund described that communication is complex, as the point is, a person exchanges messages because they want to share meaning with other people. The fourth, communication is irreversible, which mean the word already said is indelible like a permanent ink stain. And number five, communication involves the total personality. A message cannot be viewed separately from the person. Communication is more than a set of behaviours, and it shapes how a person views themselves and others [73].

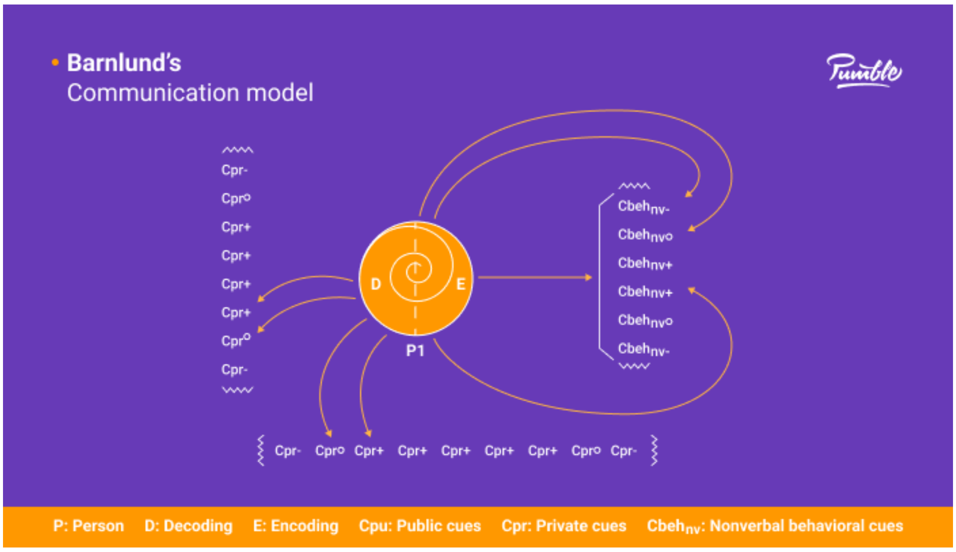


Figure 18. Barnlund's Transactional Model of communication, 1970

Figure 18. Barnlund's Transactional Model of communication, 1970 shows Barnlund's communication theory that is more relevant for interpersonal communication, including verbal and nonverbal cues and feedback [74]. This model helps develop the importance of social networking through shared meaning to analyse the communication feedback loop [75]. Moreover, according to this approach in 1999, the word communication describes the way a person creates meaning in the first place. Robert Craig has mentioned communication constitutes our social reality. In his 1999 article, he said it constitutes means to create; communication is not a secondary phenomenon [76]. Communication does not happen after those views are already in our head or after the culture has taught us norms, and socioeconomic factors have shaped us. Compared to the previously mentioned models, pre-existing meaning is not in words, and it is also not in our minds that they then communicate to share the existing ideas [77]. According to this view, when human communicate with each other, they generate those ideas together; create meaning through their interactions with others over time. Human also create our social world together that they could not have created independently. The creation of shared meaning is a collective accomplishment, in which the whole social reality is the product, the outcome of communication. Through interactions, human make or break agreements, establish societal norms or violate them through the process of communication [78].

Nowadays, the concept of communication is known as a process of exchange of facts, ideas and opinions and as a means that individuals or organisations share meaning and understanding with one another [79]. In addition, the simple definition of communication is the act of transmitting information. Moreover, information in the broadest sense of the world including thoughts, ideas and emotions [80]. There are some common areas in communication, one of them called 'rhetoric' known as the art of persuasive speaking or writing, especially in giving a speech [81]. Rhetoric word began when Aristotle wrote a book about 2000 years ago, and he mentioned that when they spoke, they had these available approaches and choices and techniques that they could use to persuade our listeners [82]. For example, how a speaker can create and share messages artfully with an audience for maximum persuasiveness. Another popular area is interpersonal communication; this area looks at one-on-one conversations and relationships and focuses typically on face-to-face interaction, like friendships and family dynamics. The area of interpersonal communication is a significant area of study that looks at both nonverbal and verbal dynamics [83].

To emphasise the meaning of communication in this study, the researcher viewed on another common area called organisational communication. The focus of discussion in this communication area is around the workplace. For example, communication is likely to happen through formal and informal networks [84]. Organisation communication is a huge area and even have sub fields within it taking shape on their own, like crisis communication, training and development and whole classes in professional communication skills [85]. More recently, the interest in how communication between designers and engineers in 4D Printing settings is really important to directly impact issues like how quickly designers and engineers create or develop 4D Printing parts. This is all about the quality of communication that influences the direction of this 4D Printing technology.

2.5 Theories of Meaning and Representation

2.5.1 Semiotics the Study of Signs

Semiotics (or semiology), by definition, is the devoted study of signs systems and symbols and their use or interpretation. In humanities, the term sign is used to talk about something which stands in for something else [86]. There are two' founding fathers' of semiotics theories: the first one is Ferdinand de Saussure, who, in (1857-1913), had a volume of work posthumously published called the 'Course in General Linguistics'. In his research, Saussure introduces this concept of the sign and suggests that it has two elements to it, 'signifier' and the 'signified' [87]. For example, in Saussure's theory, Figure 19 shows that signs are divided into signifiers and signified [88]. As Saussure was primarily a linguist, he lays it out in writing to communicate the idea that there is often no inherent link between the signifier and the signified. Semiotics deals with concrete examples such as physical signs and more abstract concepts such as denotation and connotation. On the other hand, 'signifier' can be defined as the physical forms of a sign; it can be an object, an image, a word or even a sense that can create communication that is standing for something else [89].

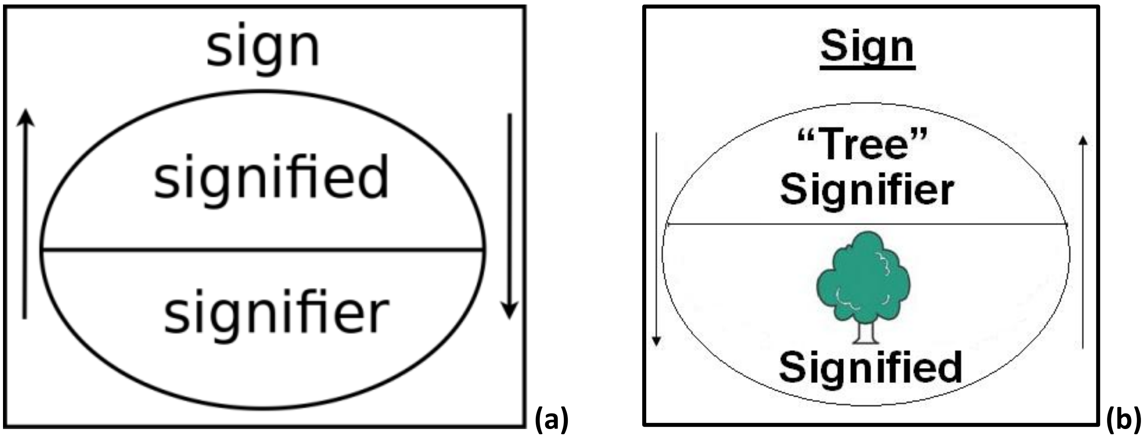


Figure 19. (a) Saussure's theory model of sign and (b) Concept and sound pattern.

In addition, the relation between signifier and signified is arbitrary and based on convention signifier. On the other hand, the 'signified' is the thing or idea that the person is trying to communicate to evoked [90]. Since a "system of signs" is thought to determine the real, the signifier cannot exist without the physical presence of the signified [91]. The key to remember is that a sign is created when the object images, words, or sounds evoke something in a person's mind. Another aspect of semiotics is 'denotation' and 'connotation'. Denotation or dictionary definition can be defined as the word's literal meaning.

2.5.2 Representation

On the other hand, connotation represents the various social overtones, cultural implications, or emotional meanings associated with a sign [92]. Many of Saussure's ideas of semiotics are very bound up in looking at linguistics, and so the second founder of semiotics is Charles Sanders Peirce lived from (1839 to 1914) looked to develop these ideas further, mainly to use these concepts outside of written or spoken language. Among his many accomplishments, he developed the philosophy of pragmatism and the study of semiotics [93]. Charles Sanders Peirce was a philosopher who is responsible for creating the general theory of signs, where anything is considered as a sign as long as someone interprets it as having other meaning other than itself [94]. According to Peirce, logic or semiotic was the means to meaning the logic of signs; it was the structure of thought since all thoughts are in signs and all knowledge was represented by it, regardless of the field of inquiry [95]. Moreover, Peirce defined semiotics as the study of signs, and the signs are anything that stands for or represents something to someone based on the highly dynamic process of interpretation. The concepts that explore semiotics evolve from the study of phenomenology, the pre-logical apprehension of the world, the essence of perception and experience [96].

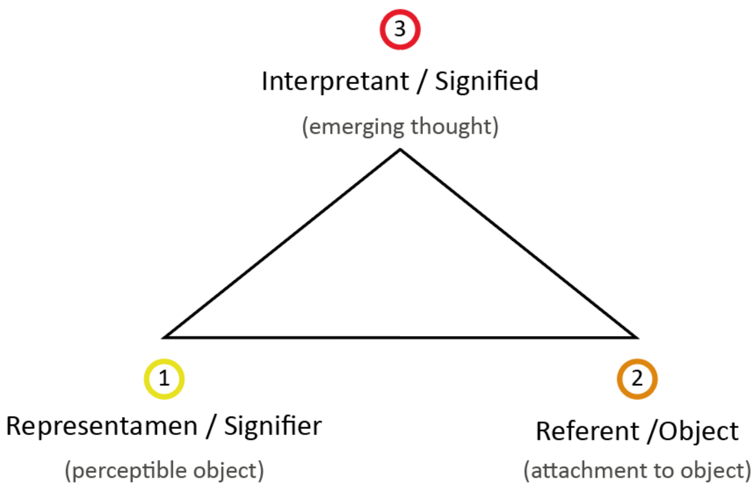


Figure 20. An illustration of The Semiotics of Charles Sanders Peirce - Triadic Model.

Figure 20. shows the method as Peirce's theory of signs explains with a sign a 'representamen' that stands to somebody for something in some respect or capacity. It addresses somebody created in the mind of a person as an equivalent sign or developed sign. The sign is some

expression of a word, sound or image that stands for its object or meaning [97]. The sign represented is the quality of a singular phenomenon or the firstness. The representamen then stands in some way for secondness. The sign's relationship with its object, essential or primary meaning. Finally, the sign is perceived and creates an equal sign in the mind of someone [98]. Peirce called that sign the 'interpretant', the sign produced as an idea in mind. Moreover, from Peirce's perspective, what crucially defines a sign is the link in the triangle that is most important in the relationship. This led him to define three different types of signs: icon, index, and symbol [99]. Another critical thing about signs is that a single object can convey many meanings, and that meaning can vary from one culture or geographical location to the next. There are many different types of signs, but their meaning is always based on a system of shared conventions [100].

However, people primarily look at things that are standing in for something else whenever people examine society and culture. Also, often look at that idea of how to communicate with each other. The understanding of how meaning is made through communication is really important [101]. As a result, semiotics can be very useful for a designer to understand and make decisions about users and their expected reactions. In addition, designers simultaneously study, analyse, and make decisions about their own communicative behaviour and strategies [102]. In addition, being able to distinguish between what signs and what meanings have a direct link to the thing that is referring to are purely socially constructed becomes a really useful concept.

Moreover, Peirce theory offers an alternative way of framing notions of a proper design science, design theory, and design artefact for the discipline of information systems [103]. By extension, this leads to an increasing number of possible ways of decoding the same sign depending on what culture someone brought up or what specific context is [104]. An icon has a physical resemblance to the idea or thing that it is trying to evoke or signify. However, a symbol is the opposite of an icon, so it does not resemble the signifier that is being represented. Thirdly, the indexes which describe the physical connection between a signifier and signified. Understanding signs then is fundamental for understanding how and why meaning gets made the way it does [105].

Icons

(a) (b)

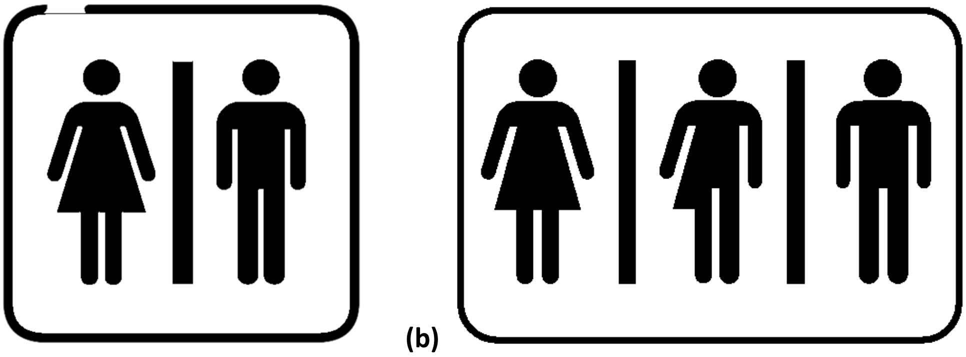


Figure 21. Male and female pictograms and abstract ideographs, with the merged pictogram and gender-neutral symbol (a), as seen on existing designs (b) [106].

The first type of sign is the icon, which is a sign in which the representation resembles the object strongly enough to be recognisable as the real thing. The word icon comes from the Greek word 'eikon', which means an image or likeness representing something else [107]. In other words, an icon is defined by the fact that their meaning closely resembles the actual thing they are trying to represent. In fact, thousands of icons have been used in our daily life without us even noticing; that is because icons are one of the powerful tools of communication. In order to create icons that successfully convey the right message to the right people, a number of key aspects must be considered [108]. In addition, by choosing the right type of icon to create, which icon generally break into three categories. The first categories of an icon are a pictogram, which is to represent something that easily recognisable. The example of pictogram used is to represent and compare data; a picture or of the original image can represent one or more pieces of data [109]. Moreover, a representation of stylised pictures that express an idea or give a concept in the minds of people to see the icon is known as an ideogram [110]. The next type of icon is a logogram, which represents a word or set of words. The chosen type of icons depends on the message that they try to convey [111]. The visual forms of icons and logograms are perceptually distinct, but they function similarly to communicate information in both linguistic and non-linguistic ways [112].

Furthermore, the creation of an icon should evoke an emotion that elicits a mental connection in the minds of individuals. This is incredibly delicate and crucial when designing an icon for an international audience. Sometimes, icons do not resemble the thing they are trying to convey, but their message is clear because people have been taught to associate that icon with the meaning [113]. While icons are universal in their meaning, they are compelling tools to convey information. A typical example shows in Figure 21 (left) an example of a symbol a male and female icons, representing the presence of toilet facilities. However, there is nothing in these signs that indicates a connection with the public toilet, but people are taught from a young age what these icons mean and know how to look for if stuck in a public place and need to go. However, considering a recent situation, designers have created a variation of the existing icon by emerging the male and female form to identify as 'gender-neutral public toilet' icon Figure 21 (b) [114].

Index

Figure 22. Smoke is an index of fire [115]

The second type of sign is the index, signify by association where the referent is the consequence of the object is not crucial to the relationship, where that indicates or stands for something else that is not there [116]. This means it can be inferred or observed, Figure 22. shows an example of indexes, which smoke is an index of fire, this is because everyone knows that smoke will not appear if there is no fire [117]. In addition, the index pattern correlates some sensory feature to something else through its absence or factual connection. The signifier is not arbitrary, but it is directly connected to some way [118].

Moreover, the important idea of the index is when people try to understand early accounts of what photography was or why is photography so special. The idea was, the status of the photographic or cinematic image as a document is tied to its indexical powers [119]. Basically, when thinking about the index and the indexicality of photography, it is a special and precise way of understanding something, such as the idea of a photograph of an apple, where a person will think it is not just a representation of an apple. Still, it is also a document of that apple existed in the past. This is called as indexical, a type of sign that shows the evidence for the existence of a particular material thing it refers to [120].

Symbol

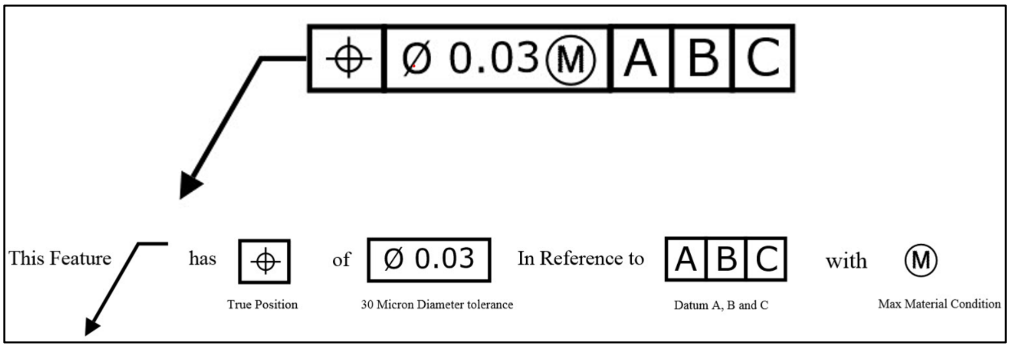


Figure 23. Example of symbol used in GD&T' feature control frame' consists of four sets of information [121]

The final type of sign is called a symbol, representing a means of complex communication that often has multiple levels of meaning. To start with, the word symbol come from the Greek word '*symbolon'* means token or watchword. A symbol is a representation of a concept or idea. A symbol is a shape is a flat two-dimensional (2 Dimensional) (2D) object that can be defined as an image, object or others [122]. Symbols also used shapes to create something that has to be learned to disseminate information. In this case, there is a relation between the concept of symbol and metaphor, and as an example, when looking at the shapes of trees, to create a symbol, the symbol will represent the forest [123].

However, a symbol has to be particularly cautious when created for an international audience. The fundamental of symbols would be to convey information even in a different country that speaks a different language [124]. Moreover, people learn what symbols mean over time, which symbols are learned culturally; this explains why cultures can develop different and unique traits [99]. Words are also a symbol, where writing requires knowledge that allows the association of a word to its object or meaning. Spoken words must be learned because sound has no natural relationship to its object. For example, different languages will have different symbols for the same object [125].

2.6 Communication barriers in 4D Printing

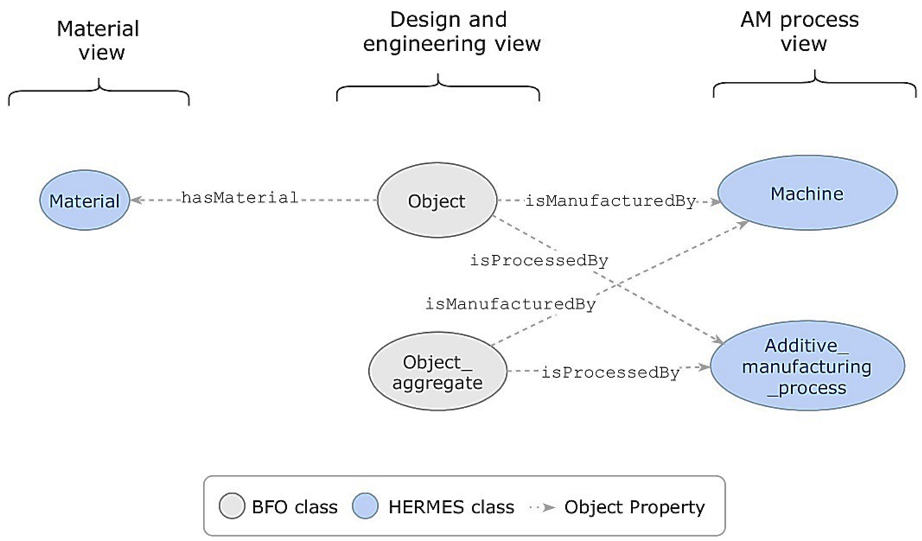


Figure 24. Semantic connection between designer and engineers in the 4D Printing design process [67].

The concept of communication is a simple yet effective way of sending a message to a receiver. However, some problems or barriers prevent people from communicating effectively. Figure 24 shows the design or engineering perspective is a strategic place that aims to understand the various aspects of 3D printing comprehensively. It also exhibits semantic relationships between objects and Additive Manufacturing processes. This strategic place is additionally equipped with dedicated classes focused on the development of 4D printing related to communicating the design process. One of the most common ways to identify these types of barriers is by separating them into external and internal categories. In this way, it can help in developing effective communication strategies.

Language barriers

One of the most common barriers preventing people from effectively communicating is the lack of a *common language*. This issue can be addressed by non-verbal communication, and it is a type of communication that can be used to persuade and empower people. It can also help improve the understanding of the sender's message. Another common issue that can prevent people from effectively communicating is using *over-complex language* [126]. Visual communication, such as graphs, images, symbols, etc., in a presentation can clarify the speaker's message. This visual aid can be combined with other verbal techniques to help the listeners understand the message. Using non-verbal communication in a group or interpersonal conversation can provide a more effective and clear understanding of the message.

Standardisation of communication

A well-defined procedure and standardization system can help boost communication within the design process. Standardisation can help improve the efficiency of the various aspects of a process, such as design and manufacturing. Having well-defined documentation can also help ensure the information flow is carried out efficiently. One of the most important advantages of process standardization is that it can provide a well-defined set of procedures. This can help the design process develop effective and efficient operating procedures. For example, standardised graphical symbols, icons, and diagrams in technical drawings, CAD etc., are used to communicate the 3D Printing process [127].

Differences in perception and viewpoint.

The relationship between designers and engineers might lead to barriers in communicating 4D Printing. Various barriers can prevent people from communicating effectively. One of these is the lack of understanding of the different roles and responsibilities involved in the process. In organizations with a lack of knowledge about the roles and responsibilities of communication, people may not know what is expected of them. According to an article, designers believe engineers should interpret design methods faster, better, and more accurate. On the opposite side, engineers often believe that the designer's design specifications should be more precise than necessary, which can result in more expensive manufacturing processes [128]. The communication framework is a vital part of any communication process. It can be used to depict various ideas and concepts simply, such as through visual representations or symbols. These models are commonly used to explain concepts and ideas in a way understandable to people. Although they are helpful in various ways, the communication model is not free from limitations. The concept of a communication model represents the process that involves symbols in communication. However, if it does not significantly explain the messages, it is difficult for people to make an informed decision.

2.6.1 Existing ways to communicate 4D Printing

This study investigates the barrier of communication area in the design process so that the user designers and engineers can communicate the 4D Printing design process effectively with the established or identical features. The meaning of standardisation is the process of creating a protocol to guide the creation of development and implementation of technical standards. It involves gathering and analyzing the opinions of various parties, such as government, business, and interest groups. It can help improve the quality, safety, and interoperability of products. In addition to improving the quality of products, standardization can also help facilitate the normalisation of previously custom processes. Furthermore, from the deeper investigation into the 4D printing communication area, it can be seen that this direction of study has not yet been fully explored.

One of the most important factors that can be considered when it comes to the design and message content of the symbol is the printing temperature and the layer thickness. This will affect the recovery time and electrical resistance of the finished product. Compared to the samples with different printing factors, the difference in the temperature and the layer thickness of the finished product has a significant effect. Some examples of communication ways to communicate the 4D Printing process were selected from random journal papers. However, some examples from random research papers show in
Figure 25 to Figure 30 that the researcher uses no standardisation system or tool for communicating the 4D Printing elements while explaining the experiment process.

The study found a lack of standardization when communicating or presenting the 4D Printing elements in the design process. It was specified that no studies or data had been found in a relationship for effectively communicating 4D Printing technology. This problem can be misleading for designers or engineers when interpreting the content of communicating with one another. Another issue with this process is that there is an ambiguous communication representation used for indicating the elements, which can be misinterpreted by the users.

Currently, there is no standardized communication regarding the design process for 4D Printing. This lack of communication can affect the quality of the information presented to the designers and engineers.

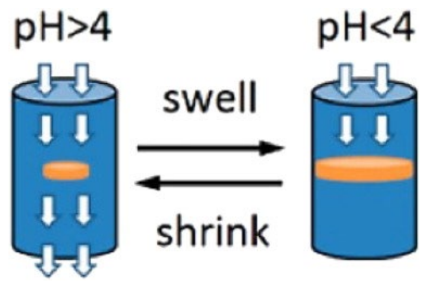
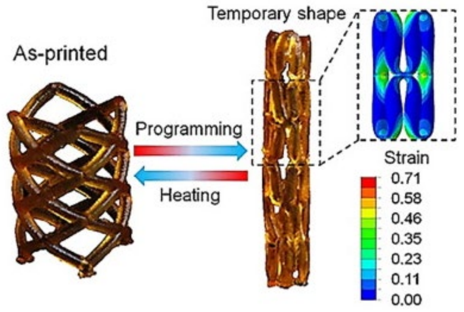
	Example 1	Example 2
Stimuli and Shape-changing behaviour		

Figure 25. Example 1 is how experiments communicate the shape-changing of expansion using pH-responsive level [129]
Figure 26. Example 2 is how experiments communicate the shape-changes of expansion using heating [130]

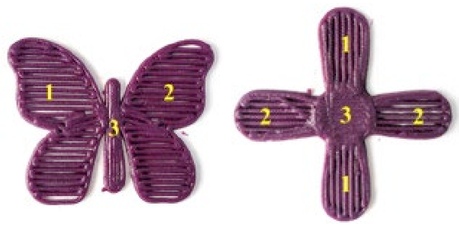
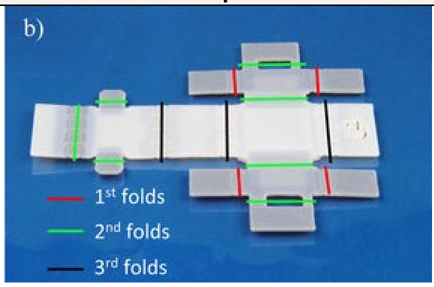
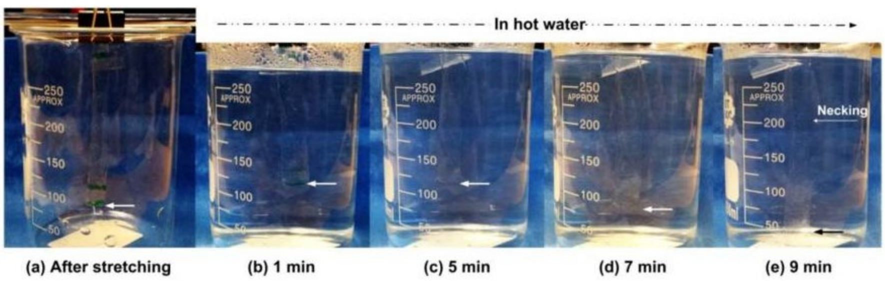
	Example 1	Example 2
Timed sequence		

Figure 27. Example 1 Image samples of shape changes deformation with timed sequence by [131]
Figure 28. Example 2 Image samples of shape changes deformation with timed sequence by [132]

	Example 1
	

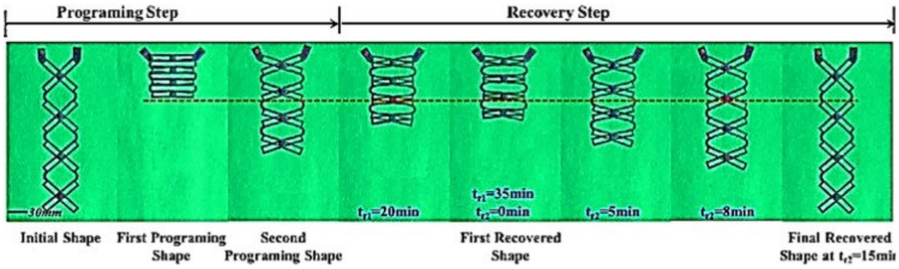
Recovering time	**Example 2** 

Figure 29. Example 1 is how experiments communicate the time for the recovery process [133].
Figure 30. Example 2 of how experiments communicate the time for the recovery process [134]

In a bridge to the communication gap between engineers and designers in communicating the 4D Printing design process, a method of selecting communicative tools is being explored, as it forces communication in specific directions. Otherwise, this could limit the amount of unrelated information introduced into the conversation and conflict with either practice's capacity. In this way, some challenges in selecting the correct information to transfer can be eliminated as long as designers and engineers can understand and engage with a specific system. Moreover, either party can select that system and ensure both communicate the information in this form of understanding. From the analysis of the tools used by both practices, it became apparent that either designers and engineers used the same tools in very different ways or used the same tools in very similar ways. This is quite natural because both engineers and designers are concerned with producing physical objects.

Despite the fact that designers and engineers have a number of tools in common, this study introduces the 4D Printing symbol as a communication tool compared to other methods to ease the communication barrier between designer and engineer by using shape and forms to disseminate information. Throughout this thesis, by using 3D Printing symbol design as a reference, this study has identified the practices and attitudes of designers and engineers toward user involvement in graphic symbol design at the conceptual design stage. Differences between engineers and designers were also discussed. Furthermore, related to the investigation of this study, the focus of the communication study has more on the functionality and usability of inspirational interaction design and semantic meanings conveyed by the pictorial or visual display. To support this statement, the primary function of visual displays is to utilise specific conventions to communicate information using semantic displays.

2.7 Communication in the design process

> *"Engineers are not the only professional designers. Everyone designs who devises courses of action aimed at changing existing situations into preferred ones. The intellectual activity that produces material artifacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state. Design, so construed, is the core of all professional training; it is the principal mark that distinguishes the professions from the sciences. Schools of engineering, as well as schools of architecture, business, education, law, and medicine, are all centrally concerned with the process of design. There are many ways in which designers solve problems, but they are by no means the only ones who do that. Design is not the same as problem-solving, but it does involve certainly contributes to addressing issues that are perceived to be problems, as well as developing new or altered products, services, or environments to respond to those identified as problems".*
>
> *(The Sciences of the Artificial. Book by Herbert A. Simon, p. 130, 1969).*

According to Herbert Simon, in his book The Sciences of the Artificial, design is a meta-discipline that can be applied to all professions [135]. He claims that every professional designer has the same goal of creating courses of action that are designed to change existing situations into desirable ones. The intellectual activity that is involved in creating material artifacts is similar to the one that is involved in the design of a medical treatment. In addition to engineering and architecture, other fields such as education and law are also heavily involved in the development of design [136].

In simple words, it means that the design should be meaningful, which implies that if a designer designs a product that is easy for the user to use and can help them achieve their goals, they will be satisfied and happy. For a designer to explain and share their work clearly and convincingly, it is crucial to communicate the ideas and thought process behind the work, be it with the team, the stakeholder, or the end-users. The main goal is to understand the usage domain and keep designers and engineers communicating their ideas on the same page with a shared vision towards achieving the end goal. The primary way to engage in communication design is to create communication tools. To ensure designers and engineers could effectively communicate the information the design requires.

2.7.1 Communication Tools

Table 3. Summary for the type of communication.

Types of communication	Descriptions for the type of communication	Communication features
Verbal Communication	Includes exchanging information through spoken words, written messages, or sign language.	An oral conversation such as talking through phone calls or face-to-face skype calls.
Nonverbal Communication	Often called the heart's dialect, it is the method of transmitting messages without using words.	Body language or sign language.
Written Communication	Interaction that uses written words can be referred to as written communication.	Messaging via 'Whatsapp' or using email/letters.
Formal & Informal Communication	*Formal*: A structured and official flow of information between leaders, employees, colleagues, and other people at various levels in the organisation.	Official discussion, facts, and professional discussion.
	Informal: A spontaneous and unofficial flow of information between leaders, employees, colleagues, and others.	Unofficial discussion, gossip, suggestions, and personal conversation.
Visual Communication	It is an important concept where two or more people can effectively communicate their thoughts, messages, and ideas.	Design (symbols and brand design) and Illustrations.

Communication occurs in three different ways: verbal, nonverbal and visual. People tend to take for granted the exchange of information that occurs in a conversation. Understanding the various methods involved in this process is very important in professional settings and business settings. As shows in Table 3. visual communication is mainly interchangeable with communication design and strategically telling a story to an audience. For example, communication design is specifically used when discussing the strategy of expressing information through visual design.

2.7.1.1 Verbal communication

By communicating, a person conveys information and interest. Also, verbal communication is one way for people to communicate face-to-face; some of the critical components of verbal communication are sounds, words, speaking and language [137]. There are two types of verbal communication: oral communication and written communication [138]. Oral communication involves speaking, what is said, and listening to what is heard by alternating turns to speak [139]. Oral communication can be divided into verbal, paraverbal and nonverbal components. The verbal component is the content of the speech, which includes the choice of words and the theme of the speech and its organisation. The paraverbal component refers to the voice; it involves, among other things, flow, volume and intonation. The nonverbal component encompasses body movement, gestures, posture, and others [140].

Furthermore, successful and effective speaking depends on the harmonisation, concordance and coherence of the verbal, paraverbal and nonverbal components. It is hard to state that one of the three aspects is more important than the others [141]. Some researchers have tried to quantify each of the three components used in communication and the number very enormously from one researcher to another. Moreover, it has been found that a contradiction between components causes a perceived lack of credibility in the person speaking and nonverbal communication tends to dominate the other components [142].

2.7.1.2 Non-Verbal communication

To define non-verbal communication is all of the rest from verbal communication, which means it is how the person looks, gestures, facial expression and others [143]. On the other hand, a more academic definition of nonverbal is exchanging information through non-linguistic means [144]. Therefore, not all communication is done with words; for example, nonverbal communication is when someone texts, they use emoticons either instead of words or as an embellishment to what they wrote. In 1967, Dr Albert Mehrabian and his colleagues published a study claiming that only 7% of a message's meaning is communicated in verbal communication, as shown in Figure 31 [145]. The remaining 93% of the meaning comes from nonverbal communication, which is divided into 38% from voice and 55% from what he called 'general body language' [146]. Another example, the experiment of teaching the English language performed by the foreign teacher, in which the result showed students responded positively toward nonverbal communication using [147]. Regardless, it is undeniable that nonverbal communication has a huge impact on whether someone actually understands what another person is communicating [148].

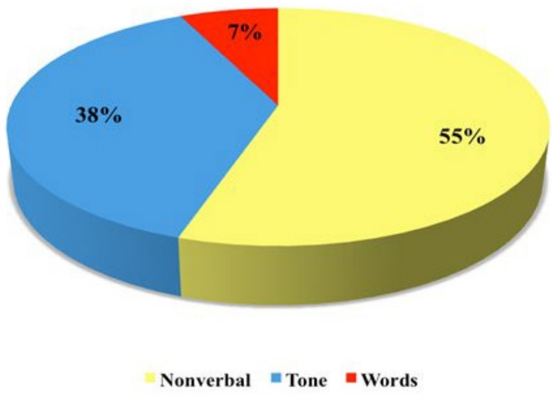


Figure 31. Mehrabian's Breakdown of Face-to-Face Communication [86]

Furthermore, the importance of nonverbal is through emblems and illustrators, which have a specific agreed on meaning. Emblems are nonverbal cues with a universal meaning within a specific culture [149]. For example, in American cultures, the 'thumbs up' gesture means someone did a good job. However, emblems are decided by a particular society, which means that a gesture could be very different from what it denotes in another culture. Then again, emblems can have agreed-upon meanings, and they are inextricably linked to their cultural context. In contrast, illustrators use automatically and subconsciously to illuminate a word in speaking, where it is used to illustrate the verbal message, they accompany. It helps a person paint a picture that to express the words, it is also not explicitly taught to a human or tied to a culture, but often unique to the person, timing and situation.

2.7.1.3 Visual Communication

In order for a visual message to be easily understand by a third party, it is important to consider the core messages that need to be conveyed and the most appropriate way to convey them [150]. A mark should not have to stutter along its intended pathway but should be able to move unchallenged and make an effective contribution to visual message. There are various types of communication that can be used in visual form, such as maps, drawings, and signs. These can help reinforce verbal communication and provide the audience with something to look at. Visual aids can also help a speaker recall important details and convey the message being presented [151]. Visual communication graphically represents information to efficiently and effectively create meaning. Limited text is used to explicate the meaning, which means users such as designers and engineers should not have to rely on the text to understand the visual, instead the visual will speak louder than words.

2.8 Design Representation in Communication

Table 4. Categories of Communication Representations

Figurative representations	**Visuals**	Three-dimensional images Photographs Illustrations / Drawings Schematics pictures
	Graphic symbols	Pictorial symbols Abstract symbols Arbitrary symbols
Non-figurative representations	**Verbal symbols**	Verbal descriptions Nouns or labels Letters or characters
	Non-visual and non-verbal representations	Sounds Odours and scents

The rise of digital communication has led to emerging the visual communication graphically represents information to efficiently and effectively create meaning. Furthermore, it is the transmission of ideas and information through video, animation, images, GIFs, and other visual media. When necessary, the real key with visual communication is 'limited' text is used to illustrate the meaning. Meaning by the limited is, a person should not rely on the text to understand the visual; instead, the visual should always speak louder than words. In addition, visual communication is a more effective way to organise important information and share it with the audience (whether that is coworkers, team members or external clients) There are two main visual communication products: visual storytelling and information visualisation. Visual storytelling provides a complete narrative through visual content, where it makes someone through the beginning, middle and end.

The advent of digital communication has given rise to visual communication, which graphically depicts information to efficiently and effectively convey meaning. Visual communication involves the transmission of ideas and information through various media like video, animation, images, GIFs, and more. The key to successful visual communication is to use minimal text, allowing the visuals to speak for themselves. This form of communication is highly effective in organizing and sharing critical information with audiences, including coworkers, team members, or external clients. Visual storytelling and information visualization are the two primary products of visual communication. Visual storytelling narrates a story through visual content, while information visualization presents data visually without drawing conclusions, allowing viewers to interpret the information themselves [152] [153] [154].

Infographics merge modern design and universal iconography to communicate information, while motion graphics offer a straightforward method to convey complex messages [155] [156]. The visual representation of intricate information in various forms lies at the heart of design tasks. This approach not only uses practical skills but also suits designers' cognitive styles, enabling design researchers to leverage their visual communication skills to support written arguments [157] [158]. Visual representation acts as a communication tool for designers, externalizing various ideas through the process of visualization. Both designers and engineers play essential roles in 4D Printing technology, defining the requirements for integrating information across design, manufacturing, and inspection processes [159].

Freehand sketching, an age-old technique, was taught to designers and engineers before the introduction of Computer-Aided Design (CAD) software and hardware. This approach has several advantages, such as enabling brainstorming during the initial stages of the design process and facilitating the generation of numerous ideas quickly. Additionally, freehand sketching allows designers and engineers to visually communicate their ideas before refining them with CAD software for fabrication and manufacturing [160].

2.8.1 The influence of symbols on communicating 4D Printing

In 4D Printing, effective communication between designers and engineers is crucial [161]. This exchange involves sharing ideas, concepts, imaginations, behaviors, and written content. However, individual worldviews, cultural differences, language, and background can complicate the communication process [162] [163]. Clear images, sketches, or diagrams can overcome language barriers and serve as effective nonverbal communication tools [164]. Symbols can quickly disseminate, store, and retrieve large amounts of information and cut across language barriers, making them particularly useful within the context of 4D Printing [165] [166].

Table 5. Geometric Dimension and Tolerance (GD&T) symbol

Type of Tolerance	Symbol	Geometric Characteristics
Form Controls	⏤	Straightness
	⏥	Flatness
	○	Circularity
	⌭	Cylindricity
Profile Controls	⌒	Profile of line
	⌓	Profile of a surface
Location Controls	⌖	Position
	◎	Concentricity
	⌯	Symmetry
Orientation Controls	//	Parallelism
	⊥	Perpendicularity
	∠	Angularity
Runout Controls	↗	Circular Runout
	⌰	Total Runout

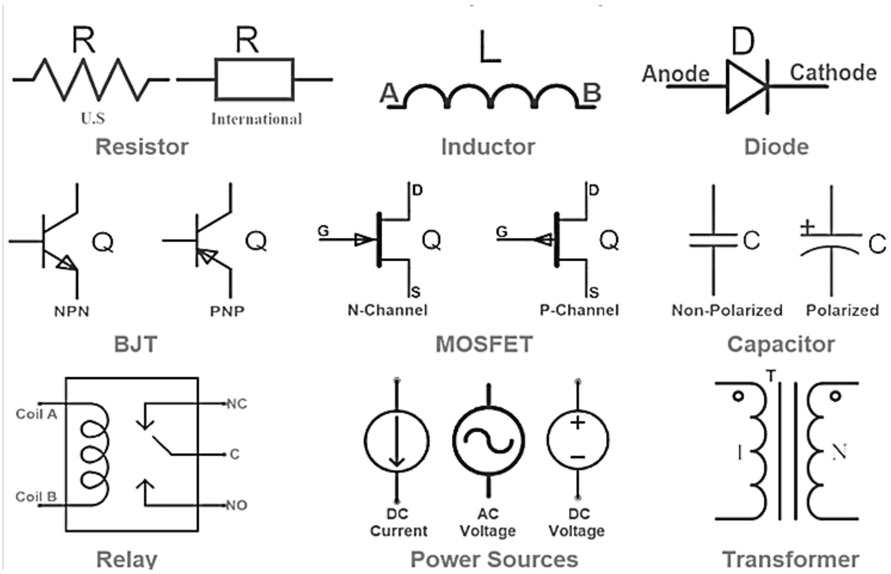


Figure 32. The symbols for some of the more common electronic components in a schematic diagram. [167]

Various symbols play essential roles in different fields, such as engineering drawings, electronic schematics, and the periodic table of elements [168] [169] [170]. Geometric Dimension and Tolerance (GD&T) symbols are standardized by the American Society of Mechanical Engineers (ASME) and help engineers convey design intent for parts and features as shown in Table 5 [171]. Electrical and electronic devices are represented by schematic symbols, which are standardized by the American National Standard Institute (ANSI) and the International Electrotechnical Commission (IEC) as shows in **Error! Reference source not found.** [185][186]. Isotopic symbols, or isotope notations, represent chemical elements and their isotopes in the periodic table.

In this study, the design of symbols as communication tools for 4D Printing is explored and supported by relevant theories such as semantics, semiotics, and universal language. The semantic triangle of meaning, proposed by C.K. Ogden and I.A. Richards in their book "The Meaning of Meaning" (1923), describes the relationship between representations and the things they represent. This model provides a theoretical foundation for understanding how symbols communicate meaning, enabling designers and engineers to collaborate effectively in the development of 4D Printing technology.

2.8.2 Semantic triangle of the symbols meaning

To strengthen the arguments regarding symbol design as a communication tool for 4D Printing. For example, how these symbols were designed and selected or screened, all the design decisions were created with relevant theories, such as semantics, semiotics, universal language and others. Semantic distance is the proximity of the pictorial icon representation to its intended meaning [172].

Figure 33. René Magritte, "The Treachery of Images" (1929) [173]

Moreover, semantic distance in the context of the symbols refers to the closeness of the relationship between a symbol and the function of what it represents [174] [175]. This is further reinforced by other researchers, where the semantic distance is the correlation between what is depicted in a symbol and the function that it should represent [176]. Semantics can be defined as the study of meaning in a human language. Furthermore, this is the way for a person to identify areas where miscommunication can arise. In this study, the semantic triangle of meaning relies on the idea that languages and systems of languages are built on symbols. The language here means the most prevalent symbols humans use to create and share meaning about the world. Therefore, the symbol is a written, spoken, or visual representation and stand-in for or represents something else.

In 1929 the days of René Magritte, an artist who is painted "The Treachery of Images", where the painting shows an image of a pipe, but underneath it, written in the French language, *‘Ceci n'est pas une pipe’* which means ‘This is not a pipe’ as shows in Figure 33 . This is the ambiguity between a person rational understanding of representation and the immediate automatic response that something is what it looks like gets at the fundamental message of Magritte painting; that is, a representation can construct powerful reality for people. However, representation is not the same thing as reality, there are two parts to the relationship between symbolism and meaning. The first part is a model of communication called the ‘semantic triangle of meaning’ used to describe the relationship between representations and the thing they represent. The second part is a sign, the representations of meaning, and a significant sign called symbols, which comprise most of how people communicate with each other.

Furthermore, C. K. Ogden and I. A. Richards in their book “The Meaning of Meaning” in 1923, present the idea of the semantic triangle of meaning as shown in Figure 34. It is a basic theoretical formulation for how representations of meaning communicate that meaning. There are three elements as part of the semantic triangles of meaning, first is the sign, the representation of word, sound, and image (the picture of the pipe). Next, the referent the object being represented, as an example related to Magritte painting, she paints a picture of a pipe that is supposed to represent a pipe, the pipe being the object that is being represented. Then, the third is reference, where which happens in a person's mind when perceiving and engaging in cognition to try to make sense of either the sign they were seeing or the referent they are referring to.

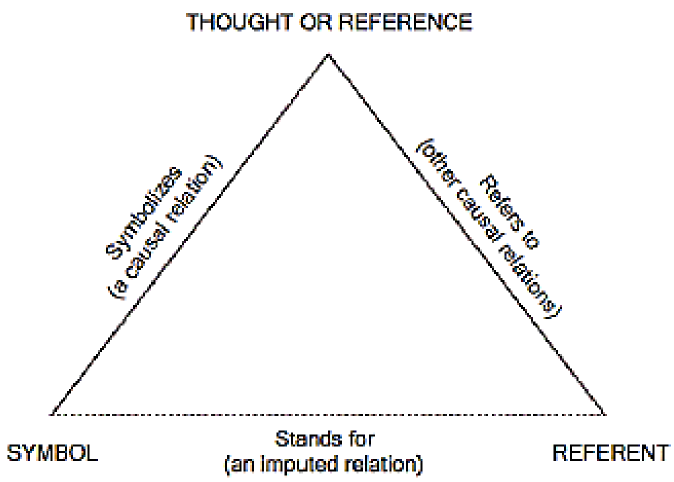


Figure 34.Ogden and Richards’ meaning (or semiotic) triangle “The Meaning of Meaning” 1923 [177]

All the various connotations, beliefs, related values, experiences, knowledge and those things in a person mental database. The model's implication on the bottom of the triangle is a dotted line between sign and referent. Ogden and Richards are trying to communicate that the relationship between symbol and referent is unstable, which means that the same sign can be used to represent any number of different referents. Furthermore, the relationship between references and the rest of it the relationship between references and signs or between references and referents can be both individual and social. In addition, people that live in communities and larger societies and cultures who live together use these signs that refer to same reference often, develop symbol systems in which going to share a lot of these references. For this reason, one of the fundamental things that makes communication possible is because people share these various cognitive perceptions; what is meant by a certain sign that comes into mind when encountering a particular referent is the shared cognitive understanding that enables people to communicate [178].

2.9 Limitation and Research Gap

After exploring the trends and literature review related to the topic, as presented in the literature review section, past studies have found that communication usage in design significantly influences transmitting ideas in the design and manufacturing process. Furthermore, a significant body of literature found that visual communication characteristics and lack of information availability significantly affect the development of products and manufacturing. However, based on the initial research review of related literature, it was found that no studies have been conducted on the topic of how communication tools can be effectively used in designing the 4D Printing part. Furthermore, practical methods and tools for communicating the design process have been given limited attention in developing 4D Printing technologies. As a result, no precise communication tool has been laid out to combine the aspects and thus address the specific communication needs.

Current barriers include having an understanding of material science and simulation. A multi-disciplinary approach is needed to tackle these current challenges. Communication as an important aspect between different users should also be investigated (and perhaps standardized). Supported by a point made by (Kumbakonam and Rani, 2016) [163], regarding sharing information. Communication is usually the transmitting of messages between individuals that allows those involved to exchange thoughts and opinions, reflect on experiences and, where necessary, seek affirmation. This theory was used as a reference. 4D Printing is growing in awareness and the potential for new applications. Various limitations can be overcome by carefully considering the design and message content of the symbol. These can be done by assessing the message content during the design phase.

2.10 Chapter Summary

Researchers identified a literature gap where no standardised communication tool is used in designing 4D Printing products. In this literature review chapter, the communication barrier discusses how and what is the existing ways designers and engineers communicate in presenting the 4D Printing process. Recently, theoretical and practical research topics on 4D Printing have gained increasing interest from numerous researchers in various disciplines and practices. There is a wealth of information regarding 4D Printing technology since it is a current topic of interest in the technology field. However, finding related and reliable sources of information on how to communicate 4D Printing was a challenge for us as there were very few and limited studies. For this reason, the primary research is on visual communication and work to generate 4D Printing ideas accessible using the proposed communication tool.

Furthermore, researcher work to develop theoretical underpinnings for automated Charles Sanders Peirce signs semiotics during methods. Pierce was a philosopher and one of the pioneers or 'Founding Fathers' of semiotics theories in the 18th century (see Section 2.8). He made important discoveries in fields responsible for creating the general theory of signs. The Pierce theory of signs visually represents sets and our relationships. Although he carried out this work centuries ago, signs and symbols were used since language did not exist. These early methods of communication have been taken seriously as an alternative to formal visual communications. Pierce's theory has been influential in this study to create ways to communicate the shape-changes behaviour of 4D Printing visually. Designers and engineers have actively changed how they design 4D Printing parts in which they communicate, address problems and ultimately generate solutions together.

In order to bridge the communication gap between engineers and designers in 4D Printing, a method of selecting communicative tools is being explored, as it forces communication in specific directions. As a result, you may limit the amount of unrelated information that can be introduced to the conversation and may interfere with the practice abilities of either participant. In this way, some challenges of selecting the correct information to transfer can be eliminated. Further, researchers investigate how the symbol can be a better communication tool for designers and engineers in 4D Printing. Based on these considerations, the study investigated the factors influencing the lack of communication in 4D Printing. The idea of creating a symbol as the communication tool in the 4D Printing design process is to achieve information delivery and improve designers and engineers engagement with 4D Printing. Furthermore, from the deeper investigation into the 4D printing communication area, it can be seen that this direction of study has not yet been fully explored.

Chapter 3:

RESEARCH METHODOLOGY

Chapter 3

RESEARCH METHODOLOGY

Chapter content

Chapter Three discussed the methodology of this research. The research combines qualitative and quantitative methods known as *'mixed-methods'*. The mixed-methods are concerned with observing and collecting insight in order to affect its outcome. The quantitative methods focus on exploring new investigations and having a more specific perspective of previous research findings (qualitative); so that the research data can be measurable. It also discusses data collection and data analysis methods and summarises the validity and reliability of this research using the design research method framework.

3.1 Research Methodology

The term research methodology is commonly referred to as a system of models, guidelines, procedures and techniques used to investigate the finding or results of a research problem [179]. As a consequence, it involves adopting guiding principles that direct the research. It is important to emphasise the context of research methods since it avoids philosophically conflicting approaches. The principles and procedures used in implementing a research methodology can be adapted to different procedures, such as data collection and analysis [180]. These guidelines are designed to help researchers avoid making mistakes such as using data analysis techniques that are not compatible with the sampling methods that will not answer the researcher's research questions. Although many research methods can be used in a study, it is important to carry out the methods according to a specific research methodology.

According to the field of social research, topics related to human and social life are commonly included in the scope of its studies. It is a process that involves exploring and understanding the various aspects of the social world [181]. Two main approaches to social research are experimental and empirical methods to collect information from individuals with a particular point of view [182]. Deductive research uses scientific experiments, where a test is carried out under controlled conditions to test a theory or hypothesis; an empirical approach, on the other hand, focuses on analysing data to solve a social problem and is referred to as inductive. Therefore, to evaluate the communication barrier for the 4D Printing product, empirical methods were used to collect and analyse data. This study also explores the potential communication tools in 4D Printing. Therefore, exploration-based empirical research is being conducted. As the chapter opens, it discusses general research approaches before moving on to design research approaches and design-related research methodologies.

3.2 General Research Approaches

3.2.1 Research Approach

The research aims to discover what is known about a given topic or phenomenon and what can be done to improve it. It is an integral part of investigating a situation or solving a problem. Although research can take many forms, there are three primary methodologies to execute research ideas called the nature of research: exploratory, descriptive, and explanatory. In terms of the research purposes, research questions are developed. *Exploratory* research explores the initial research into a hypothetical or theoretical idea, which is the first research conducted around a problem that has not yet been clearly defined [183]. Exploration research, therefore, aims to gain a better understanding of the exact nature of the problem and not to provide a conclusive answer to the problem itself; and enables a researcher to conduct more in-depth research later on. *Descriptive* research attempts to describe and explain while providing additional information about the topic [184]. In addition, it focuses on the *'how many'* and *'what'* accepts the *'why'* questions. It expands knowledge of a research problem or phenomenon by describing it according to its characteristics and population. *Explanatory* research tries to explain the relationships between variables. Meanwhile, explanatory research focuses on the *'how'* and *'why'* of research questions and is often based on experiments [185].

3.2.2 Research Strategies

In this section, this study align the approaches discussed in the literature, building on the previous discussion about methods, applied and research areas. The research strategies are simply a plan of how the researcher aims to achieve the research goal [186]. The research approach influences design and provides an opportunity to consider the benefits and limitations of various approaches available to the researcher. Two approaches are available in the research strategies, known as *inductive* and *deductive*. The *inductive research*, the theory is generated from the ground up [187]. In other words, from the collected data, these studies tend to be exploratory in terms of their approach. On the other hand**,** *deductive research* starts with established theories and builds on them with collected data. Therefore, these studies tend to be confirmatory in approach [188].

There are two primary approaches to data analysis, known as qualitative and quantitative methods. *Qualitative* research generally employs an inductive methodology, beginning with the gathering of empirical data and subsequently developing concepts based on the data to achieve dependability. As a result, it is more subjective in nature and frequently employed to gain a comprehensive understanding of complex situations, providing a detailed depiction of the context. On the other hand, *quantitative* research follows a deductive approach, starting with an abstract concept and then devising ways to evaluate the outcomes. This method emphasizes the use of numerical values and statistical analysis to examine intricate data. [189].

Mixed methods explore the research questions as this method combines the advantages of both the quantitative and qualitative approaches in a single research design better [190]. In addition, it also stated that using a mixed-method approach is better than only following the quantitative or qualitative methods [191]. For instance, quantitative and qualitative methods commonly support data analysis and usually focus on generating reliable results. A mixed-methods design was adopted to investigate and explore the qualitative approach to the developed set of hypotheses. Then, once those hypotheses are established, the researcher uses quantitative methods to test them.

3.3 Design Research Approaches

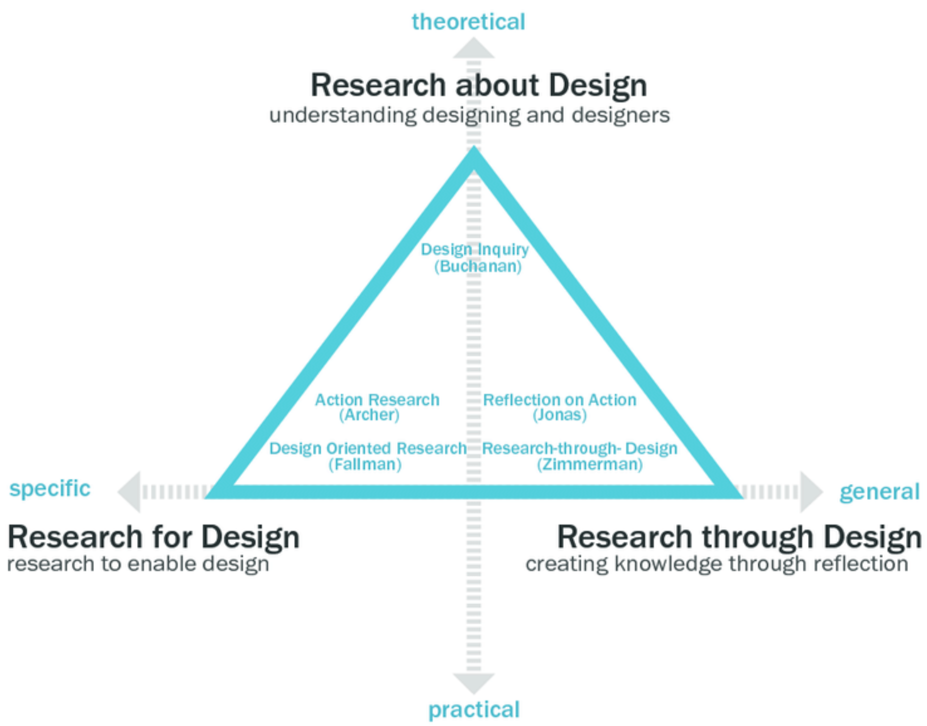


Figure 35. Research for Design, Research through Design, and Research into Design (inspired by / adapted from Frankel and Racine, 2010)

The design research framework is constantly evolving due to the increasing number of new approaches and techniques being introduced. While some of these new methods are complementary and compete with one another, the goal of the design framework is to drive and inspire discoveries in the sharing of ideas, tools, methods, and resources. In 1993, Sir Christopher Frayling defined three different categories of design research shows in Figure 35

[192]. These include *research* ***for*** *design*, *research* ***through*** *design*, and *research* ***into*** *design*. The following definitions can define this classification. Research *for* Design aims at the visual design to improve a design or product's aesthetic appeal design. Research *through* Design *(RtD)* concentrates on the design process as a research method [193]. It aims to generate new knowledge by analysing the current situation in the form of a design and then proposing an improvement in the future. It involves deep reflection on understanding the situation, problem and context around the people involved. Research *into* Design focalise on the study of design and various design theoretical approaches towards understanding design practice and knowledge.

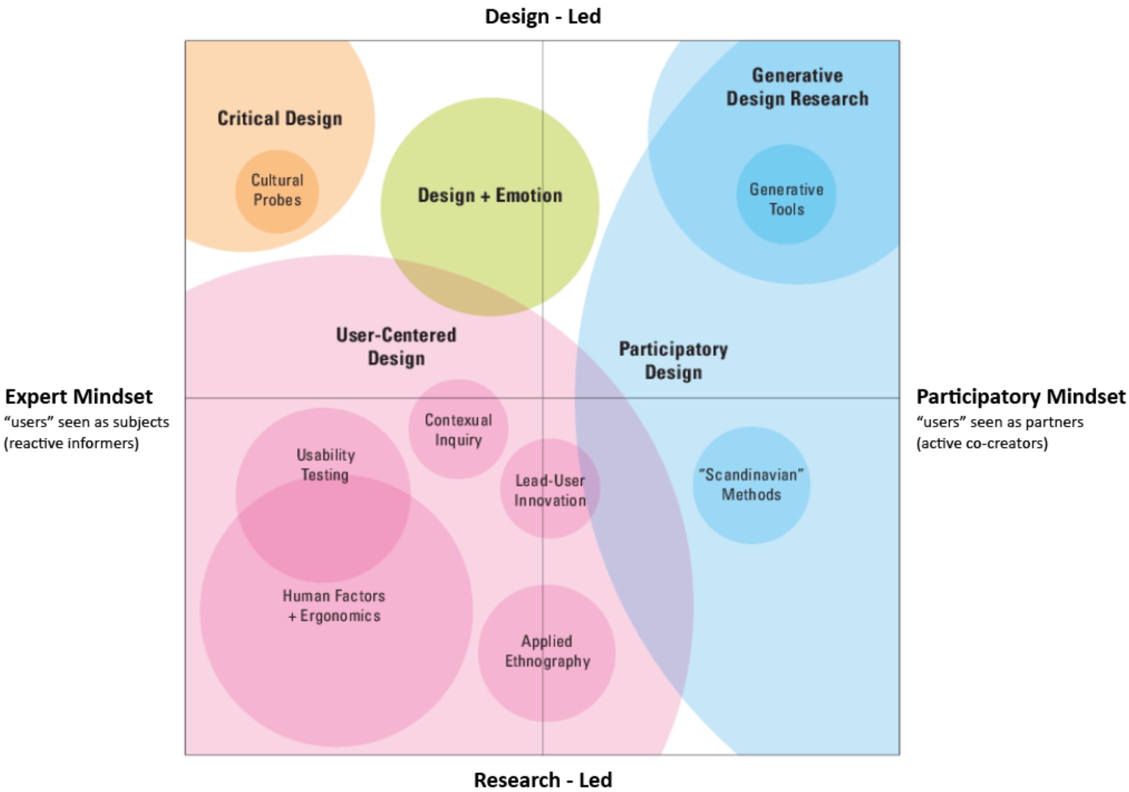


Figure 36. An Evolving Map of Design Practice and Design Research, adapted from (Sanders, 2008).

Christopher Frayling's (1993) categories apply to all art and design research processes depending on how research methodology relates to design practice based on creating new knowledge [194]. Meanwhile, Cross (1999) offered a taxonomy of design research by identifying three categories: *design epistemology', 'design praxeology'* and *'design phenomenology'* based on: people, processes, and products [195]. *Design epistemology* is a theoretical investigation of design ability, believing that the human ability to design is a valuable and complex trait; this discipline focuses on studying how people design [196]. *Design praxeology* is focused on the strategies, tools and tactics that design practitioners use to facilitate and practice their work. This discipline mainly studies the design processes and the development of techniques that aid the designer. *Design phenomenology* focuses on the knowledge accumulated during a project's development stages. This includes the knowledge that is contained form and configuration of artefacts within the finished product. Moreover, it allows designers to develop effective solutions to design challenges [197].

Currently, there are two dominant mindsets in the map of practice design research, as shown in Figure 36 [198]. On the left side of the map, the *expert mindset* shows a culture characterised by experts involved in designing for people. This is because these individuals believe they are the experts when designing for others. On the other hand, on the right side of the map *participatory mindset* shows a culture characterised by participatory researchers who value the people as the true experts in working, learning, and living [199]. The dominant mindset in design research is that of the researchers who value the people as co-creators of the design process. A map of design research is a tool that can help visualise the relationships between various design tools and approaches. It can also help hold a domain long enough to see the various aspects of the process.

The concept of a participatory design zone is also represented by the varying approaches carried out within the *research-led* and *design-led practices*. This approach involves the people most likely to benefit from the designed products and services. The concept of the participatory design zone aims to involve everyone in the design process [200]. One of the critical characteristics of this method is the use of physical artefacts as thinking tools, which are commonly used in the design process.

The goal of the *generative design* bubble (top-right corner) is to inspire people to think critically about the current state of affairs and develop solutions that can benefit the community [201]. The term *generative tools* refer to a methodology combining the design language with the designer's direct visual communication or interaction with the researcher or stakeholder groups. This process is carried out through a shared design language. The concept of the design language is generative because it allows people to express their ideas in a limited set of stimulus items. This method is designed to provide a framework for the people who the design process will serve.

3.4 Design Research Methodology

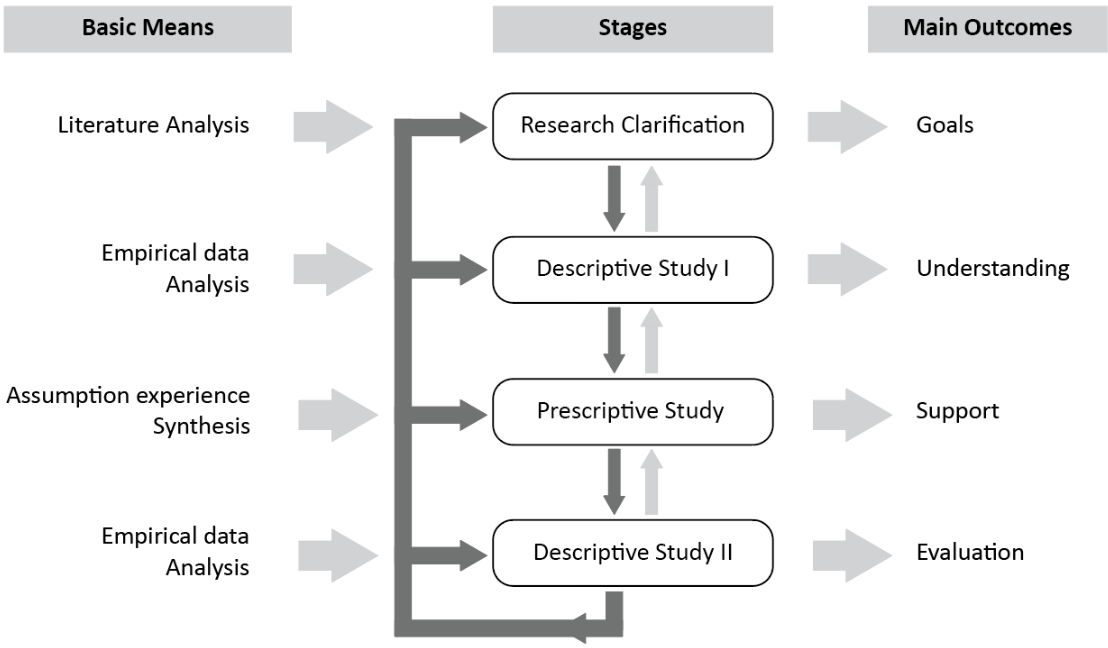


Figure 37. Design Research Methodologies Framework adapted from (Blessing and Chakrabarti 2009).

This section explains the main concepts and stages of the selected design research and the need for a standard methodology. The goal of design research methodology is to develop and validate theories and models related to the phenomenon of design. It also aims to improve the design process by developing and validating knowledge and methods that can help improve the chances of a successful product. Research design includes strategies, methodologies, procedures, techniques, software tools, guidelines, information sources, etc. The researcher utilises it to carry out a scientific study. It is a comprehensive coexistence of already identified elements and any other information or data leading to a good result.

In this study, the researcher selected a *Design Research Methodology (DRM)* that supports a more rigorous approach to improve design research efficiency and effectiveness. Design Research Methodology (DRM) is an approach and a set of supporting methods and guidelines to be used as a framework foresign research [202]. The word 'support' is used to cover the possible means, aids and measures that can be used to improve the design. The focus of Design Research Methodologies (DRM) follows a set of principles in order to identify the main issues and develop and evaluate the support tool as a strategy to resolve them. The study results contribute to the knowledge base related to this field.

According to Blessing and Chakrabarti (2009) Design Research Methodologies (DRM) support process is divided into four phases: Research Clarification, Descriptive Study I, Descriptive Study II, and Prescriptive Study. Figure 37 shows the connections between these phases: *basic means*, *stages* and *primary outcomes* that lead to the conclusion of this study. In the first phase of DRM, the *Research Clarification (RC)* focused on a literature review which involved potential research goals and problems. In the second phase, through *Descriptive Study I (DS-I)*, the researcher aims to gain a deeper understanding of the factors that influence the design process. This step involves identifying the various factors that can affect the design process. In the third phase *Prescriptive Study (PS),* from the findings of *(DS-I)* or *(DS-II)*, the study can then start to develop design support. This phase involves creating tools, guidelines, and methods that can help reduce or enhance the influence of various factors. Finally, the fourth phase of the study, the *Descriptive Study II (DS-II),* examines how empirical studies can be utilised to evaluate the effectiveness of the design support.

3.4.1 Reliability and Validity of a Research

The quality of research is based on its validity and reliability, which leads to generalizability. Reliability refers to whether the data collection techniques and analytic procedures would reproduce consistent findings if repeated on another occasion or if another researcher replicated them. There are three different validities of research: construct validity, internal validity, and external validity. Construct validity concerns the extent to which the research measures what it claims to measure. Second, internal validity is established when the research demonstrates a causal relationship between two variables. The third is external validity, which concerns whether a study's research findings can be generalised to other relevant settings or groups. The study discussed various perspectives on design methodologies in information technology. These perspectives could address the question of validating the design process in research. The map can also organise the various design research tools and methods to help reveal potential futures.

3.5 Selected Research Approaches and Methodology for this Research

As stated earlier, the research defined in this thesis is a combination of social research (see section 3.1) and design research (see sections 3.3 and 3.4) because people are involved in a real-world context while improving a current situation through design [203]. The various design and generic research methods used in the study were thoroughly reviewed in previous sections. The research conducted in this thesis is 'research *through* design', a study of 'design praxeology' and falling in the area of 'design exploration'. Table 4 below summarises the adopted generic and design-related approaches in this research.
The research purpose is considered *'exploratory'* to understand an issue better and potentially develop the theory or set of hypotheses. 4D Printing utilises additive manufacturing methods to print stimulus-responsive products subjected to specific stimuli. However, finding related and reliable sources of information on how to communicate 4D Printing was a challenge as there were unaddressed or not taken or limited attention for these studies.

In this study, the research strategies use the *'mixed-methods'* approach to bring qualitative and quantitative research to gather the better [190]. Qualitative research utilises data that is not number-based, focusing on words, concepts, perceptions, or ideas. It is used to investigate the softer side of things, such as exploring and understanding people's perceptions, ideas, or feelings. Therefore, qualitative data can be used to develop hypotheses and theories from the ground up, in other words, an *'inductive'* approach. This involves conducting interviews and focus group sessions on getting participants to talk about their ideas, perceptions, and understandings regarding the communication toolkit for 4D Printing.
In contrast with this, quantitative research makes use of numbers and statistics. Typically, quantitative research measures differences between groups and or relationships between variables and tests hypotheses. Therefore, it is more objective and takes a *'deductive'*

approach. For example, it is used to measure what percentage variable when choosing the 4D Printing communication symbols in conducting surveys [204].

Table 6. Research approaches selected in this research.

	Reviewed research approached	Adopted research approaches
Research purpose	Exploratory Descriptive Explanatory	Exploratory
Research strategies	Qualitative Quantitative Mixed-Methods	Mixed-Methods
	Deductive Inductive	Deductive Inductive
Design research frameworks	Research into design Research through design Research for design	Research through design
	Design epistemology Design praxeology Design phenomenology	Design praxeology
Design research and design practice map	User-centred design Participatory design Generative design Design +emotion	Generative design

In this thesis, the design research frameworks fall in the group of '*research through design* and '*design praxeology*'. This type of approach focuses on the creation of new knowledge instead of the project solution. The development of design tools to communicate the 4D Printing design process was also refined through design praxeology intentionality. This type of research aims to explore the process of developing outcomes. The reason is that the design process of the conceptual framework and toolkit for communicating 4D Printing is the focal point of this research study. This research is a design practice that includes a conceptual framework and toolkit to guide engineers and designers in communicating while designing 4D Printing parts. This research investigates the communication barriers between designers and engineers in designing 4D Printing parts. To bridge the communication gap between engineers and designers in designing 4D Printing parts, a method of selecting communicative tools is being explored, as it forces communication in specific directions.

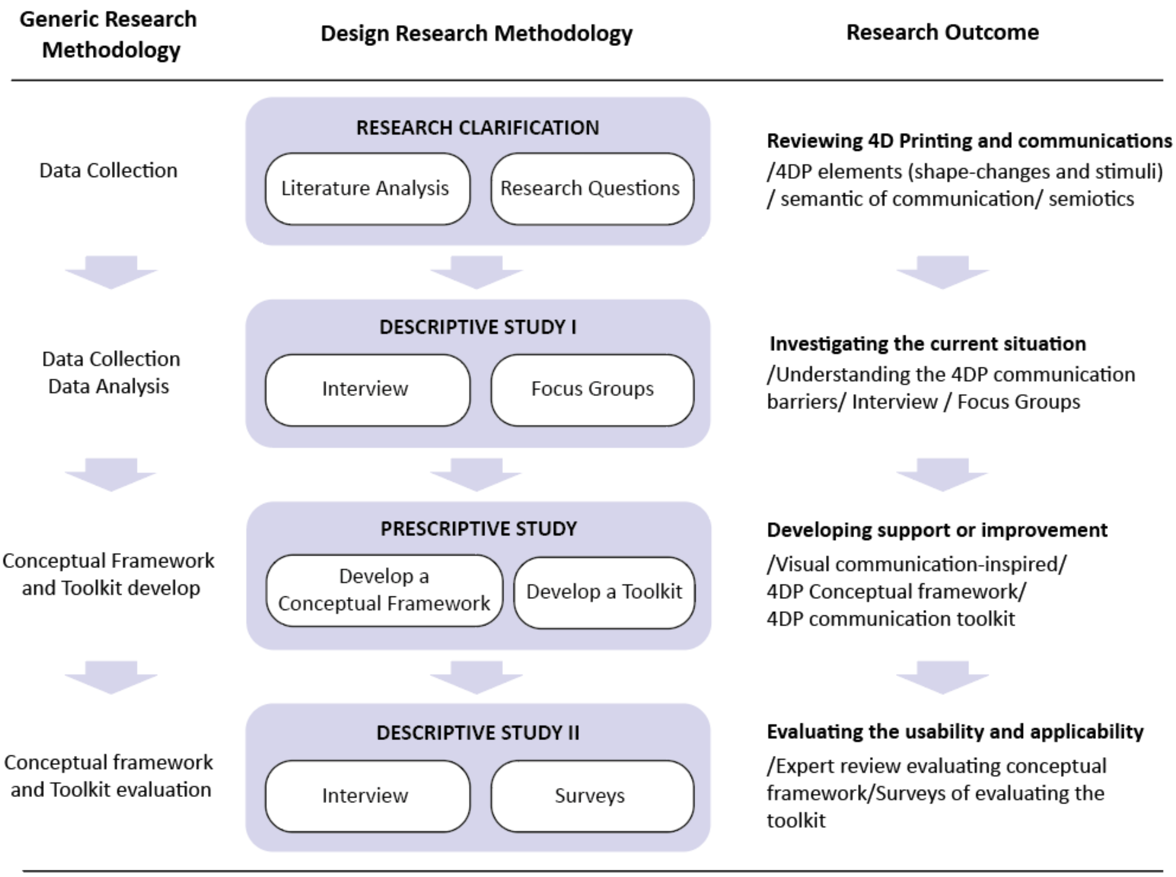


Figure 38. Adopted Framework for Design Research Methodology (DRM) in this PhD research.

This thesis was carried out using the ***Design Research Methodology (DRM***) framework. In design research, the two main objectives are to formulate and validate models and theories to describe the design phenomenon and develop and validate knowledge, methods, and tools using these models and theories to improve designs [205]. The DRM approach to answering the research questions is illustrated in Figure 38. The main elements of the design research methodology are: identifying the problem, developing a solution, and evaluating the solution's effectiveness. A suitable design research methodology should help guide the selection and implementing of appropriate methods and techniques. This process is carried out through frameworks and steps designed to guide the study. A comprehensive descriptive and prescriptive literature study revealed that conceptual framework design could significantly affect the 4D Printing communication toolkit design process.

3.6 Development of the Design Research Methodology

The method of investigation is held through both qualitative and quantitative research. In this section, the researcher explained how the Design Research Methodology framework was used and how various steps were taken to answer the presented questions. These questions were selected to investigate the issue of how to improve the design of 4D Printing parts through communication. The questions presented in the study were analysed and then formulated to suggest solutions. This type of design research can be done by collecting quantitative and qualitative data (mixed methods).

3.6.1 Research Clarification Phase

Data Collection methods applied: Literature review

The first stage of the study focused on the two research questions. This research clarification phase has been conducted through literature reviews to answer the first research question and mainly focuses on 4D Printing, Theory and Analysis of Communication. A literature review is a systematic method commonly used to collect and synthesise previous research [206]. The main objectives of this phase are the identification of research aims, questions and hypotheses and the formulation of an overall research plan.

The literature review aims to answer the first question of the study by reviewing the various aspects of 4D Printing, which also focuses on three aspects: the 4D Printing background, the semiotic and semantic communication and the ideas for a 4D Printing communication tool. The background of 4D Printing includes primary data of (product application and 4D Printing elements). Following the communication part, theories of (semiotics and semantics of visual and linguistic) in communication barriers related to research (design solutions for communications) were reviewed. The study results were then used to develop design tools that can be used to produce 4D Printing parts. Then, 4D Printing elements, which are highlighted from various research and those which are chosen from representation assessments, are elaborated. Finally, potential representation assessments were described. Figure 39. shows the literature review map for this research thesis.

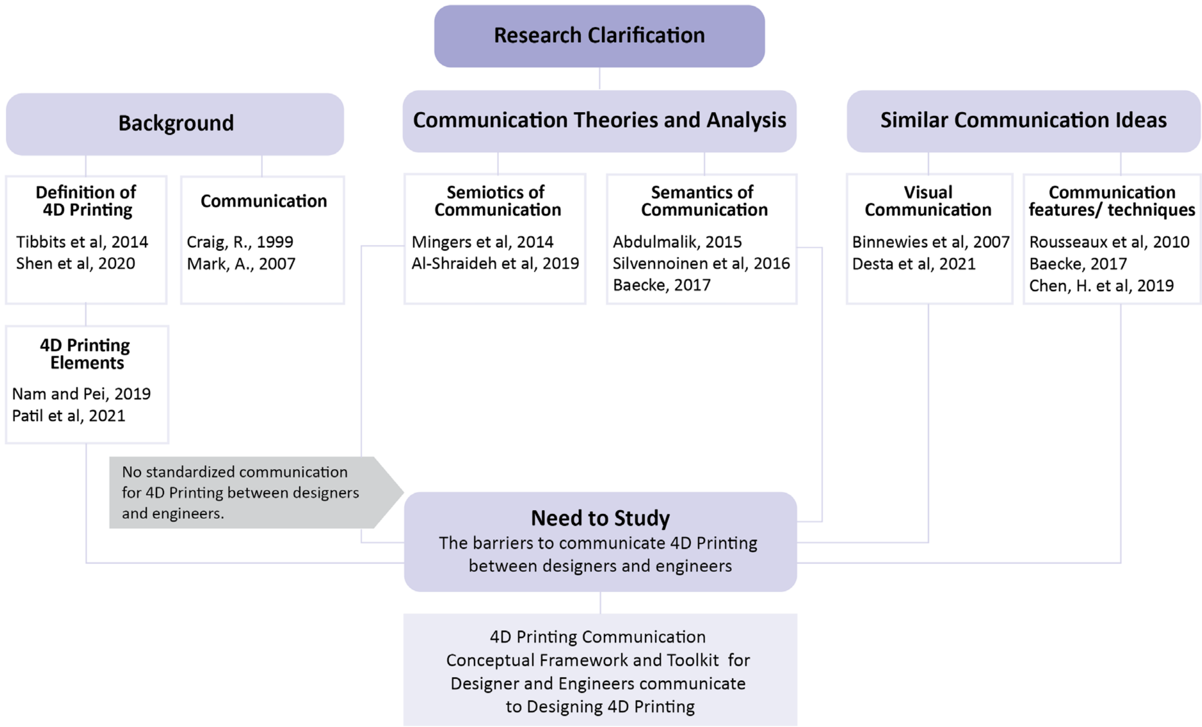


Figure 39. Thesis research map for literature review

The research study gap is that there was a lack or no attention had been given to standardised communication on how to improve the communication between engineers and designers when it comes to designing 4D Printing parts. This issue was also addressed by developing a conceptual framework as a guide to creating a 4D Printing design toolkit to help engineers and designers communicate effectively during the design process of their products. In addition, this research ensured that the majority of cited and references had the most recent publication dates, going back no further than 2010, as 4D Printing is a relatively new field. A few researchers were included from previous decades to establish foundational concepts that continue today. After considering these factors, the researcher analysed the data itself. When examining the data in the articles, the researcher looked for statements that indicated proper research procedures being conducted.

Before the broader study started, the study was reviewed by the Research Ethics Committee of the College of Engineering, Design and Physical Sciences (CEDPS) at Brunel University London before conducting any research. Finally, in examining qualitative and quantitative data, the researcher examined the collection procedures data to verify that the study had adhered to practices that would ensure reliability and validity. In identifying sources for this literature review, multiple databases were used. Initially, Brunel Library and Google scholar, etc., were utilised to initial sample what type of journals and articles were available.

3.6.2 Descriptive Study I

Data Collection Methods Applied: Semi-structured Interview + Focus Groups

Research Question 1: What are the existing barriers between designers and engineers when communicating about 4D Printing?

Semi-structured Interviews

This study begins by discussing possible reasons what is the barriers in communicating 4D Printing. However, the proper understanding of participants' experiences is limited, especially concerning in-depth qualitative research. The researcher conducted individual semi-structured interviews to investigate this study to gather information, knowledge, and practice experiences. A semi-structured interview aims to balance structured interviews, emphasising the researcher's conceptualisations [207]. By conducting an individual semi-structured interview, a problem with a specific issue can be understood by interviewing participants with relevant, factual and professional information [208]. In a semi-structured interview as qualitative research, the interviewer's questions can be added or omitted as necessary, based on the situation during the interview. This method allows the researcher to investigate that can provide relevant information by gathering data analysis from participants. Since the research is an exploratory study of the 4D Printing design area, there is barely any information available on how to support effective 4D Printing communication design. purposive sampling method has been used to recruit participants for the study dealing with a limited number of primary data sources that can contribute to this research [209]. The results from the interview were visual and audio recorded, and then analyse qualitative data transcribed by coding/ indexing method [210].

Focus Groups

In order to gain a better understanding of people's opinions and perceptions of new concepts or ideas, two focus group was conducted. This qualitative focus group investigated the existing communication tools designers and engineers used to communicate 4D Printing. A focus group is an excellent method for the early stages of research to gather as much information as possible to answer the research questions [211]. Moreover, a focus group allows data collection by interaction with participants to expand their knowledge and share their. Participants were recruited to participate in this focus group and were selected using selective sampling based on participants' knowledge and expertise of the study under investigation for both focus groups [212].

Observation

This focus group study observed participants thinking and sketching signs of progress, which is how the idea may develop for further investigation about the communication barriers in 4D Printing through design activities approach on how they communicate in determining 4D printed products. For the observations, part study, the reliability of data analysis is based on the direct evidence in the video recorded and to ensure that as little information as possible is lost [213]. Symbols in the study differ from the traditional method of recording the participants' thoughts and ideas. While letters are commonly regarded as words, they can also describe ideas or thoughts.

3.6.3 Prescriptive Study

Data Collection Methods Applied: Survey - Session One

Research Question 2: What type of design representations are the most effective in communicating aspects of 4D Printing?

4DP Design Representation Communication Tool

A survey is a research instrument that collects data from a group of people. It can be conducted to gather information about the individuals' views on a particular issue. An opinion poll or vote is the instrument survey used to determine how people respond to specific issues [214]. An online survey was conducted as part of the comprehensive study investigating and developing a communication support tool for the communication barrier in designing 4D Printing products. This stage discusses how both conceptual frameworks and toolkit prototypes can be used to introduce a phenomenon into a conceptual perspective. The survey was part of mixed-methods research in this study. Participants were reached by emails and other applications, and a snowball sampling strategy was used to recruit participants. The use of snowball sampling method is often used to collect data in a study under investigation and has a low number of potential participants [215]. This prescriptive study influenced the development of the toolkit website for communicating 4D Printing elements created to support idea-generating in the 4D Printing design process. The conceptual framework also was developed to support the right approach and methods to design a tool to communicate 4D Printing.

3.6.4 Descriptive Study II

Evaluation Methods applied: Survey Session Two + Expert Group Interview

Research Question 3: How can the communication of 4D Printing between designers and engineers be improved?

Survey - Session Two

The online web-based survey is often used to gather valuable information about populations. The quality of the data collected depends on the topic and the number of people participating in the study. Aside from the number of people participating, the online survey's design and methodology also play a role in the quality of the data [216]. In order to obtain one of the research objectives, which is to develop a framework that can explain how 4D Printing symbols enable better communication between designers and engineers, a second survey analysis was conducted. In this final stage, a second online survey was conducted with designers and engineers to get feedback in order to improve the conceptual framework and toolkit, and design expert interviews were conducted to evaluate the usability of the toolkit. The purpose of the conducted online survey was to explore participants' understanding of the 4D Printing toolkit (symbol). Descriptive statistics were used to evaluate and describe the collected quantitative findings in this research [217].

Expert Interview

A group interview is when interviewees are more than one person, and this interview type is also called a focus group [218]. The use of focus groups has been widely used to study the experiences of individuals due to the increasing interest in focus groups, which has been considered valuable for collecting qualitative data [219]. This method is usually conducted in a social setting, which can help increase the participants' sense of belonging. A qualitative study was conducted with experts from the *British Standards Institution* (BSI) and *Technical Product Realisation* (TPR) to capture perceptions and feedback regarding the 4D Printing communication conceptual framework and toolkit. The focus group with those experts has been adopted to gather insight from the experts and evaluate the conceptual framework and toolkit. The toolkit was considered relevant and timeless from the expert's perspective.

3.6.5 Reliability and Validity of the Methods

The validity and reliability of a research study are two of the most critical factors that can be considered when conducting a study. The importance of verifying the validity and reliability of a research project is a way of demonstrating the rigor of the process and the trustworthiness of the findings. Aside from the type of research, other factors on how data are collected, analysed and interpreted are also considered [220]. The validity of qualitative research is also maintained because it allows the researcher to describe the biases researcher might have unconsciously. This type of research also allows the participants to provide their feedback and opinions. The researcher should also acknowledge the biases in the sampling process to ensure that the study results are accurate. The consistency of its procedures also maintains the reliability of qualitative research. This includes describing the steps involved in the research, the collected data, the development of the toolkit, and the participants' feedback [221].

3.7 Chapter Summary

To summarise this chapter, the purpose and strategies of the research have been clarified. To better understand communication barriers in 4D Printing, the primary data were induced based on qualitative research. The study explored the research barriers stated in Design

Research Methodology (DRM) framework. Therefore, mixed-methods research was selected to answer the research questions (Table 7). As a result, the researcher created a conceptual framework and communication toolkit to support the communication barriers in 4D Printing. Chapter 4 will explore the research strategy process in further detail.

Table 7. A framework of this research as specified by DRM

Design Research Methodology (DRM)	**Studies**	**Methods**
Research clarification	Understanding 4D Printing (Chapter 2)	Literature Review
	Understanding Communication (Chapter 2)	
	Design Research Methodologies (Chapter 3)	
Descriptive Study I	Data Collection (Chapter4)	Semi-structured Interviews Focus Groups
Prescriptive Study	Developing 4D Printing symbols (Chapter 5) Developing conceptual framework (Chapter 5&6)	Surveys 1 Surveys 2
Descriptive Study II	Evaluating conceptual framework and toolkit (Chapter 6)	Expert Interview

Chapter 4:

DATA COLLECTION

(DESCRIPTIVE STUDY I)

Chapter 4

DATA COLLECTION (PRIMARY RESEARCH)

Chapter content

Chapter Four added research activities to validate findings from the literature review regarding communication in 4D Printing and update them with the most current knowledge. The chapter explains the strategy and findings of semi-structured interviews with 4D Printing experts and the first stage of the focus group. The chapter is concluded with a list of the challenges of communication in 4D Printing.

4.1 Introduction

The study's research clarification (RC) stage involved introducing the literature review of the 4D Printing background, semantic and semiotic communication as described in Chapter 2 and research design methodology in Chapter 3. As described in the previous chapters, the second stage of DRM is the descriptive study (DS-I) explained in this Chapter 4. This primary research involved a semi-structured interview (section 4.2) investigating the communication barriers in designing 4D Printing products. It was followed by developing two sets of focus groups, focus group one in (section 4.3) and focus group two descriptions in (section 4.4), respectively.

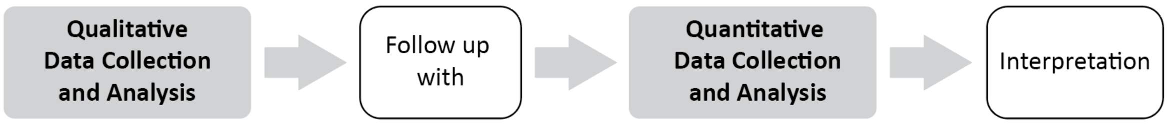


Figure 40. The adopted framework of Exploratory Sequential Mixed Methods Design (Creswell,2015)

In the last few decades, the use of mixed methods research has become a more popular alternative to traditional methods in social and behavioural science [222]. The exploratory sequential design used in mixed-methods is a two-phase method. This mixed-methods design aims at explore through developing and validating the research problem. Exploratory research refers to the initial research which lays the groundwork for future research. It is used when very little is known about the research problem [223]. In the exploratory sequential mixed-methods design starts with the qualitative data collection and analysis phase (phase-I) and followed up by the quantitative data collection and analysis data phase (phase-II), then goes into interpretation as shows in Figure 40. By using the exploratory sequential design, researcher is collecting and analysing the qualitative data and then using results from the qualitative analyses to be the foundation or to influence the quantitative data collection and analysis [224].

Therefore, in this study (DS-I), the researcher found a barrier in communicating the 4D Printing between designers and engineers from the literature reviews. As the researcher do not know the barriers yet, the researcher starts the study by conducted a semi-structured interview by interviewing 4D Printing experts and designed a focus groups as qualitative data and analysis (phase I). Then, based on the semi-structured interview and focus groups results, researcher developing surveys for measured the quantitative data and analysis (phase-II) in chapter 6. Moreover, by combining both qualitative and quantitative data, mixed-methods research can potentially compensate for the limitations of each method in understanding a phenomenon in both its general and specific aspects [225]. Furthermore, the exploratory sequential design mixed-methods, allow to explore more complete and in-depth understanding of the field or phenomenon discover in the qualitative phase. Then, associated with the variables and data collected in the quantitative phase. The idea here is that combining and integrating the strengths of qualitative and quantitative methods will make it possible to explain or support a phenomenon's complexity better [190].

4.2 Semi-Structured Interviews (Iteration One)

Interviews are commonly used as the research method to collect qualitative data for the exploratory design method (phase-I). The research interview is a type of data collection that involves the participants' thoughts and feelings about their behaviour and experiences in response to a series of questions presented to them by an interviewer. This type of interaction is often conducted verbally, making it a significant strength of the interview and a major detractor from its use in social research [226]. Aside from being able to meet different requirements, interviews are also commonly used in qualitative research to collect data in various ways. They can be used to combine data collection techniques with other methods to complete a study [227]. The semi-structured interview is characterized by elements from both structured and unstructured interviews. It usually consists of a set of questions designed to guide the discussion. In contrast, additional questions can be introduced to allow the researcher to explore the various issues raised by the participants [228].

Interviews have been recognised to be one of the best and most successful methods for collecting data from participants [229]. For this study, semi-structured interviews were conducted to allow the researcher to explore the topic related to the perceptions of and experiences with 4D Printing expertise and gather more information [230]. Each interview was conducted according to a semi-structured interview protocol that accounted for various factors, such as personal, interpersonal, and environmental factors. Although this necessarily affects the details of each interview, there are general guidelines that all interviews are expected to follow. However, specific topics of conversation considered unrelated at the time of the interview and not recorded would not be preserved for later analysis once the importance of such topics was established.

4.2.1 Participants Recruitment and Study Procedures

Researchers use purposeful sampling strategy. This sampling method used to recruit participant who can provide in-depth information, as the research have a limited number of primary data sources who can contribute to the study investigation [231]. The recruited participants should have an adequate knowledge about 4D Printing technology to accurately provide sufficient feedback for the research questions. Participants with limited 4D Printing knowledge as well as participants with long-term 4D printing experience could contribute in equally valid ways. Thus, the inclusion criteria were broad: a minimum of one-year 4D Printing experience and a knowledge with at least 40% 4D Printing practice or process. In total, seven participants were selected for the semi-structured interviews which were carried out face-to-face and over a Skype online visual-called.

Participants were contacted by researcher through email to participate and scheduled time for the online semi-structured interviews. Accordingly, the researcher arranged for the interview to take place at a time and place convenient to the interviewee. The interview began with a process of obtaining informed consent. All participants received written information on the study and indicated their consent before proceeding with the interview. In addition, the online interviews were audio-visual recorded with consent from participants, to record the communication process. Researcher asked for authorization to visual and audio record the interaction that followed at the beginning of each interview. None of the participants objected to the request, and all of them appeared to have anticipated it. Participants may have acquired this knowledge from their previous involvement in qualitative research as researchers or from the increasing use of recording devices during business meetings.

The interview consisted of seven questions where respondents were guided through the questionnaire by the interviewer, and to clarify the questions of they were uncertain. Notes were taken by the interviewer throughout each of interview session. As the interview progresses, interview questions are modified in response to the interview outline and participant answers. Furthermore, interviews were guided by key questions of interest semi-structured and were recorded and transcribed. The interview time limits were not set for the participants. The average length of each participants lasted about 30 and 45 minutes and were conducted between 7 January 2019 and 14 February 2019.

4.2.2 Data Analysis – Semi-structured Interview

As already mentioned, researcher using qualitative content analysis (QCA) to identify the findings that need to analyse in order to make informed decisions. For instance, QCA, can calculate the frequency of certain categories by adding them to text passages or by performing statistical crosstab [232]. One of the most common tasks that the researcher performs during a semi-structured interview is to analyze the various ways that the researcher approached the inclusion of the qualitative research in the research study [233]. According to (Miles et. al. 2014) interview results become purposeful and have meaning only after the data has been analysed [234]. Data collected by qualitative studies usually consists of written documents or recordings. Capturing and interpreting visual and audible data into written form is the first step in analysing process of data. These recording are transcribed into a form that can be used to study the data in detail. In this manner, the researcher was able to return to topics of interest and verify the meaning of the terminology used by the interviewee. The recording data can also be linked with analytic notes and coded. Verbatim quotations (word for word) from the discussions were chosen to provide support for the analysis [235].

In this study data were collected using semi-structured interview and analysed with qualitative content analysis (QCA) [236]. Content analysis is a technique for compressing large amounts of text into fewer categories by coding using in this study [237]. The purpose of content analysis were created by describing communication scholars to identify count and analyse how often messages and message characteristics are embedded in the text under analysis. As described, researcher first stage of data analysis was careful reading of the transcripts from the interviews. Then, to extract qualitative data for analysis from the tape recordings, began by transcribing them [238]. Therefore, researcher followed the content analysis method stages to annotate and assign labelling to summarize given information as shows in Table 9.

The first stage is to familiarize with the data from the semi-structured interview by reading and rereading to fully understand it. This process enable researcher to get a sense of the text as whole in order to start formulating an idea of what the main points are. Then, researcher start to dividing up the data into a smaller part whilst ensuring that the core meaning is still retained, this is done using coding units. A code can be thought of as a label, a name or theme that most exactly describes what this particular condensed meaning unit is about. Codes are usually one or two words long and make it easier to identify connections between meaning units [239].

Table 8. Steps involved in content analysis process

Stages	Descriptions
Data collection	Reading through or examine the data, becoming familiar with it.
Coding the data	Label or codes used to identify connections between meaning units.
Category	The data is analysed by applying the coding units, or groups of related codes.
Summary	Summarise the data in frequency table. Include a tally of the number of times that a coding unit appears.

Researcher organized and coded the data from the interviews manually and using NVivo qualitative analysis software, where the coding process was iterative. The next steps are to apply the coding units in order to sort the data into categories. A category is formed by grouping together those codes that are related to each other through their content or context for their relevance to the specific group [240]. Once the data has been coded and analysed, it need to be summarized in a frequency table with illustrative quotes which it should reflect the purpose of the research. Participants answers were summarized by calculating the percentages of categorical variables. Semi-structured interviews were transcribed verbatim from audio recordings, and transcripts for organizing and coding qualitative data [241].

One of the main advantages of using a qualitative content analysis is that it allows researchers to avoid false coding. This is especially useful when used to do statistical analysis or validating resource consisting of a structured set of texts (text corpus) is relatively small. This method can also help improve the accuracy of the results by running the inter-coder agreement test [242].

4.2.3 Results and Discussion

Table 9. Results from the semi-structured interview analysis.

Question 1: Role and experience		
Manufacturing Engineers	Product Designers	
4	3	
Question 2: 4D Printing Experience		
SMPs (Shape-Memory Polymers)	SMEs (Shape-Memory Effect)	Research
3	3	1
Question 3: How do designers and engineers communicate the use of 4D Printing?		
Web Application	2D-3D Drawing or Rendering	
4	3	
Question 4: How do designers and engineers apply the use of 4D Printing to products?		
Database/Framework	Specific Software	
4	3	
Question 5: Existing barriers between designers and engineers when communicating about 4D Printing?		
Limited knowledge	Framework standardise	CAD Software
3	3	1
Question 6: Representations/ tools most effective to communicate aspects of 4D Printing?		
3D/CAD Software	Prototype	
4	3	
Question 7: How communication of 4D Printing be developed/improved between designers and engineers?		
Design protocol tools	Communication Medium	CAD Software
3	3	1

The semi-structured interview was the most frequently deployed data collection method. Although the study's small sample size, it provided the researcher with sufficient data to develop useful and meaningful themes [243]. The analysis identified three themes based on this qualitative content analysis data, the results from semi-structured interview shows in Table 9. In addition to the underlying categories, illustrative quotes are used to describe each theme. The researcher began each interview by asking participants about their role or background profession. Most participants reported they were currently engaged and recently researching and have published their papers in the 4D Printing research area. The average of participants claimed that they were familiar and had knowledge in the area of 4D Printing practices for (3 to 5) years of experience.

Theme 1: Participants practice

This study identified *Participant's practices* as the first theme. Experiences related to 4d Printing technologies were evoked in the second questions of the semi-structured interview by asking: *"Could you please describe your experiences in the 4D Printing technology."* The interviews were read through several times to obtain sense of the whole. Then the text about the participants experiences in 4D printing was extracted and brought together into one text, which constituted the unit of analysis. The majority of participants mainly used SMPs (Shape-Memory Polymers) in their project in order to conduct an experiment with different shape-changes materials or properties for 4D Printing behavioural effects. Similarly, participants claimed that their background and experiences was focused on SMEs (Shape-Memory Effects) using stimuli to generate the 4D Printing shape-changes behaviour through a series of heating and cooling experiments.

Theme 2: 4D Printing application

Researcher searched for the following terms: (communication, language, CAD software, framework, knowledge, tools). The search terms with similar meaning were also considered in this semi-structured interview analysis. However, thread was excluded if they were unrelated to 4D Printing technologies.

> *"…the design of 4D printed products can be quite complex, especially if you have multiple moving parts in a single product."- Participant1*
>
> *"...sketches, 2D drawings, 3D CAD modeling and material renderings to communicate with engineers.."- Participant2*
>
> *"...by using a specific framework or software..."-* Participant7

In the second themes, participants were asked about *"how designers and engineers communicate the use of 4D Printing"*. Participants implied that they communicated using the context of the application. Pursuing this further, participants implied that they communicated using the context of the choosing material when creating the 4D Printing product. The choice of material indicated how the 4D Printing effect would work and its intrinsic properties. The second component of this theme concerned to *"how designers and engineers apply the use of 4D Printing to products"*. Participants mentioned they did this by identified a suitable framework to describe the product using relevant literature or by experimenting and analysing case studies. Participants also considered using database applications by building a knowledge repository of 4D Printing to assist designers and engineers in heuristic decision making.

Theme 3: Communication barriers

This theme was constructed from participants experience of barriers conducted with an experiment. According to participants, there were various reasons why there are barriers between designers and engineers when communicate in designing 4D Printed parts:

> *"There are many new design concepts in 4D printing and the technologies are different from conventional approaches. No standardization.."- Participant3*
> *"Type of CAD tools have limitations to express their requirements of product applied in 4DP technology…"-Participant2*
> *"One of the factors is there is no framework as a guideline to communicate in handling technical issues... or relating to language especially as opposed to ideas..."- Participant6*

When the participants were asked about *"what are the existing barriers between designers and engineers when communicating about 4D Printing"*, participants highlighted related information regarding the existing communication barriers, which there is no standardization tool such as CAD software to communicate the 4D Printing. Further issues identified as potential barriers, were related to the lack of knowledge about 4D Printing technology. This is because, knowledge here used to understand the information and selection of materials use in the 4D Printing, which involved a lot of trial-and-error process.

> *"…limited software that can predict the 4D Printing shape-changing patterns.."- Participant1*
> *"…for 3D modelling part, there are a lot of commercial software. For shape switching, compliant mechanism may be simulated by FEM for simple designs, but for shape memory based, it is still a challenge."- Participant3*

Concerns were raised about the importance of specific approaches when asked about "what type of design representations or tools are the most effective to communicate aspects of 4D Printing". Participants used various ways to design 4D Printing parts, and it was important to evaluate the experiment in relation to some conceptual understanding. In the final question, *"how can the communication of 4D Printing be developed or improved between designers and engineers"*, participants considered it worth undergoing technology development with new approaches of communication medium, as well as one person citing new forms of software, could help enhance the communication between designers and engineers. Participants highlighted that if correctly implemented development of CAD tools could greatly facilitate the 4D Printing design process.

Discussion

Through the interviews, it can be found that several general limitations could have impacted the findings. Although the study had a small sample size, the authors believe an adequate information power was achieved [244]. It is important to note that the interviewed participants had a diverse range of backgrounds, knowledge, and skills. Regardless of the limitations, this is one of the first studies to investigate communication barriers in the 4D Printing design process. Results from this primary study indicates the importance and highlight the need to improve the standardization of communication in the 4D Printing design process.

4.3 Focus Group: Role-Playing (Iteration Two)

This study used an explanatory sequential mixed method research design, enabling the integration of quantitative and qualitative data [245]. The process began with collecting qualitative data from semi-structured interviews, followed by focus groups for deeper understanding (see Section 4.1). Focus group research, a common exploratory research method, involves informal discussions among participants to understand human behaviour and motives [246].

Focus groups gather a small group of people to discuss a specific topic, obtaining data through group discussions This qualitative approach aims to understand people's attitudes and opinions rather than represent a broader population statistically. Researchers can then develop strategies to enhance communication phenomena understanding. [247]. Focus group discussion is frequently used as a qualitative approach to gain an in-depth understanding of people attitudes and opinion on a particular topic. The method aims to obtain data from a randomly selected group rather than from a statistically representative sample of a broader population [219]. The researcher can then use the data to develop effective strategies to improve understanding of the communication phenomena.

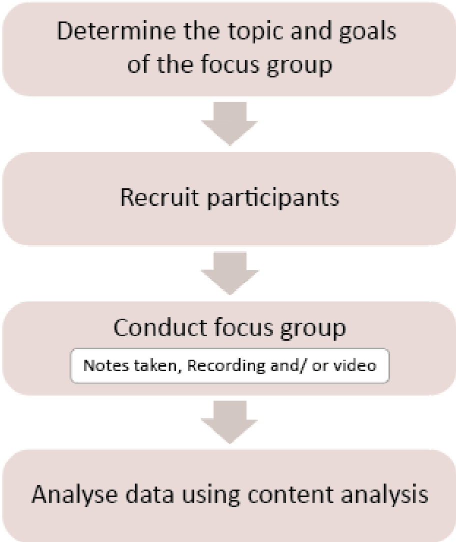


Figure 41. An illustration of the Focus Group process.

The focus group process consists of four steps, as shown in Figure 41. The topic and goals of the focus group need to be determined. Participants are recruited based on specific characteristics or demographic information. During the sessions, researchers may observe the group from behind one-way mirrors, and the audio and/or video recordings are usually taken. In addition, a note taker may also be present. After the focus group, qualitative data in the form of audio, video and written noted collected during the session is analysed and summarized using content analysis. This study aims to investigate the third research question, 'what are the existing barriers between designers and engineers when communicating about 4D Printing'.

In this phase, the study proposed an exercise called focus group – role play by using sketches as a method of data collection for research with the designer and engineer to investigate the existing communication barrier in designing 4D Printing. There are circumstances where participants may not be able to describe their actions or reactions in a way they would typically describe in a written form. This method can explore the mental representations of a category of people. More specifically, sketching can elicit information in focus groups with designers.

To maximize the effectiveness of the study, the researcher involves the participants participating in a ‘role-play’ as a data-generating approach [248]. This method allows participants to perform a specific task while being presented with a challenging yet enjoyable role. In addition, role-plays have been used successfully in communication studies; through this approach, the researchers conducted the focus group in which a study of communication between designer and engineer in the 4D Printing design process is assembled and presented with a prepared task [249]. The design of the exercise was to provide the participants to act as designers and engineers to communicate in designing 4D Printing technology.

4.3.1 Participant Recruitment

Academic researchers commonly use the focus group study method to collect empirical data based on experience and observation. This method usually sets up groups of individuals with varying levels of knowledge and attitudes. The study's objective is to determine what factors influence the participants' perceptions and opinions on a particular topic. The group process can help participants clarify their thoughts on a certain concept. It can also help researchers better understand what they think [250]. Generally, this study is faced with the challenge of finding a sufficient number of participants for a study. Since a certain topic requires a group discussion, the study's design requires that the participants participate in the discussion. Under these circumstances, the researcher only has to gather a small group of around two to five people for the study. These individuals are usually highly experienced and have a passion for the topic [251].

Since the research topic of communication barriers in 4D Printing is widely unfamiliar to most participants, it would be better to conduct the study in a small group. This focus group aimed to focus on exploring participants' thoughts, in the light of each other ideas and thoughts, on how designers and engineers reciprocally communicate with each other by using marks on paper. To pursue this study's objective, purposive sampling was adopted to recruit participants with wide range of views and experiences in design and engineering backgrounds [252]. In addition to the qualitative research, participants were selected to provide information about the research objective and their specific characteristics [253].

Participants in this focus group session were approached via a recruitment email, which involved a total of six participants were recruited. Participants were informed about the purpose of the study through emails. They were told that this study investigated the communication barrier between designers and engineers in designing 4D Printing products. The participants for this focus group study were doctoral research students (PhD) from Brunel University London with a design and engineering background. The sample comprised three designers and three engineers. The present study was reviewed and approved by the Brunel Research Ethics Online (BREO) of Brunel University London. The ethical approval process aims to ensure research integrity and that the participants understand that the information given will be kept secure and confidential.

4.3.2 Procedures

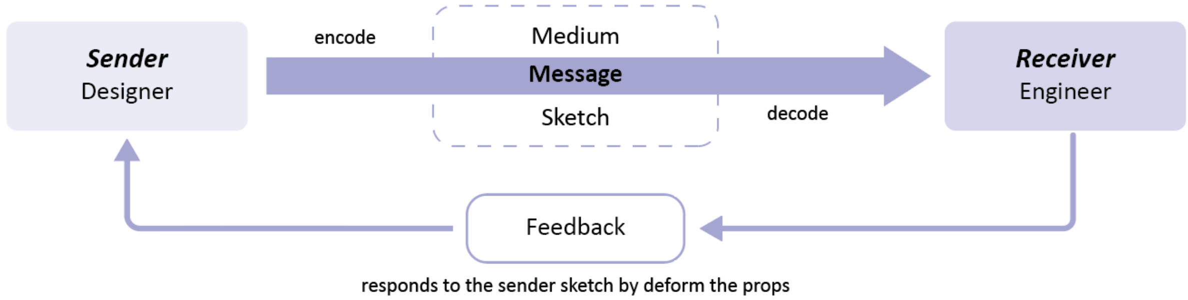


Figure 42. illustration of the communication process adapted for this focus group.

Chapter 2 (see Section 2.4) mentions four critical main elements in the 4D printing process: shape changes, timed sequence and speed [161]. Within each task of this focus group role-played, participants with design background acted as the 'sender' and participants with engineer background as the 'receiver'. The sequence of events for the focus group task was: to communicate the direction of shape-changes deformation, timed sequence, and the speed of the shape-change behaviour. This study focuses on the importance of observing designer sketches while they sketch to understand their intended meanings further.

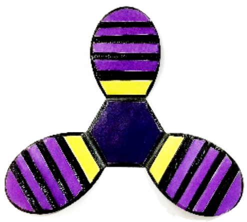
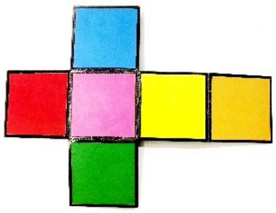
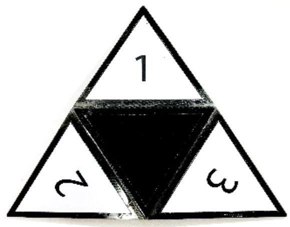
The researcher constructed an entire role-play scenario with a set of rules and roles and asked the participants to act upon it and play it out. The study defines a role-play session as a situation in which participants are presented with a case exercise while they are acting out a fictive character. To play the task, the participants first had to accept and follow the rules, settings and instructions set by the researcher. Then, they had to co-create it and give their own characters life (sender-receiver). The given instruction did not afford participants enough information to do so; they had to play it out and co-construct the setting as the session developed. The objective of this study is to collect data on observations made during focus groups with engineers and designers about the use of sketches as a technique for communicating 4D Printing. It also aims to provide a better understanding of the advantages of using sketches as a method when conducting studies with designers. In this focus group session, nine observation sessions were conducted at the Department of Design, College of Engineering, Design and Physical Sciences at Brunel University London in the United Kingdom and the Faculty of Engineering.

Upon arrival, participants were asked to read and sign an informed consent form before proceeding with the study. Participants were told they needed to act to 'represent as a sender or receiver'. The researcher divided the participants using their background study, either designer or engineer. The participant was assigned into three paired groups (one designer and one engineer in each group): the sender, the person who sketched, and the *receiver,* who interpreted the sketching.

> **Sender:** Participants in this group (designer) need to read and understand the instruction given by the researcher. They need to communicate with the receiver visually by sketches to show how the 4D Printing part react to the main three elements: shape change, timed sequence and speed.
>
> **Receiver:** As a receiver, (engineer) then demonstrated using the 3D object provided to interpret what they understand from the sketches done by the sender.

At the beginning of the focus group session, the researcher took around 20 minutes to introduce the study and lay the foundations of the study to participants, including the study's goals and procedures. The researcher itself facilitated the focus group study, and all sessions occurred on the same day. The study specifically refers to a set of procedures that are designed into the structure of the study, Figure 42 illustrates the layout of how the focus group study was conducted; this study imitated the communication process (see Section 2.6).

Table 10. 3D Printed objects represent as the 4D Printing elements.

Object 1	Object 2	Object 3
		
Shape-changes	Timed sequence	Speed

The focus group consisted of three tasks which based on the three main element (shape-changes behaviours, timed-sequence and speed) in the 4D Printing process [254]. Researcher acted as a silent observer and taking note of the activity throughout the process. The entire activity took about one hour long for each focus group. In this task, participants were asked to communicate the three main 4D Printing elements. As shown in The researcher itself facilitated the focus group study, and all sessions occurred on the same day. The study specifically refers to a set of procedures that are designed into the structure of the study, Figure 42 illustrates the layout of how the focus group study was conducted; this study imitated the communication process (see Section 2.6).

Table 10, participants were provided with the material made of 3D Printed objects as a '*prop*' used to represent the 4D Printed shape-changes behaviours. The deformation of *shape-changes* was represented in with Object 1, an order of the *timed sequence* in 4D Printing process was represented with Object 2, and the rate of *speed* of 4D Printing movement represented in Object 3.

The purpose of using sketches as a method in this study is that by choosing a familiar format that fits their basic communication, designers and engineers use sketching to create a graphical representation of their ideas. This can be done to quickly present their concepts that are related to the communication barrier. Using sketches can help decrease the barrier that designers and engineers in design experience when they communicate with each other. As part of the focus group process, each participant is not allowed to talk with each other during the focus group session. The participants were not timed and were given sufficient time to complete all the tasks. In total, nine sketches were collected over 3 hours of sketch time. Sketching time for each drawing varied from 30 minutes to over an hour, depending on the participants' time to think. The average time taken to complete one task for the focus group was approximately 45 minutes.

4.3.3 Data Analysis and Results

Data were collected using content analysis, which includes interpreting words and images from various documents, audio, or other types of media. It aims to determine how the words or images are used and in what context. Moreover, it allows the researcher to conclude a hidden perspective or behaviour. Participant observations occurred on 3 hours basis during the entire focus group sessions. The two methods are used to estimate the approach of a comparative study where the participants are matched with a single control [255]. The usual matched-pairs analysis considers the pairing, while the regression adjustment uses a set of continuous variables to model the pairing with the outcome. Moreover, it is more efficient when the sample size is small.

Focus Group – Task 1

This section describes the sketch used to collect data during the focus group session. To facilitate a focused and fruitful study, the researcher set up a focus group session to capture and identify new ideas. As mentioned, these focus group sessions are divided into three tasks. In the first task, participant (sender) was asked to draw or sketch the communication 4D Printing ‘shape-change behaviour’ to describe it to another participant (receiver). Participants selected as a sender (Participants 1, 3 and 5) give instructions using sketches to receiver participants (Participants 2, 4 and 6) as shown in Figure 43.

Presentations and discussions related to the second and third tasks were followed similarly. Participants were divided into three groups; the question was structured into different questions for the interview session. Task 1 communicates deformation for 4D Printing, which requires participants to play roles in communicating by sketches in alteration of form or called shape change behaviour in the 4D Printing process. The concept of drawing or sketching has been discussed and deployed as an integral part of various artistic forms. It can also be used to record or communicate visual information.

Task 1 - How to communicate ‘shape-changing’ in 4D Printing	
	
Designer as the ***sender***	Engineer as the ***receiver***

Figure 43. Tasks 1 – How to communicate ‘shape-changes’ in 4D Printing

4.3.3.1 Result and Analysis for Task 1:

Group 1: Figure 44 shows how Participant 1, as a sender, represent the deformation in Task 1. Participant 1 used numbering to show a step-by-step approach. She also mentioned that arrows point to the written notes as a description to ensure that Participant 2 as the receiver, understands her sketches' direction clearly. To communicate the shape-changing behaviour of 4D Printing, arrows can be used to indicate the direction of deformation on a 3D object. This technique can be used to deform the shape of an object, such as a flower, in a way that imitates the behaviour of 4D Printing. Participant 2 (receiver) feedback is that the added detail such as arrow and numbers in the sketches gives the receiver more information about the representation of the 4D Printing shape-changes.

Results from Task 1, which analysed the finding from role-played to communicate 'deformation' through sketches, were discussed below:

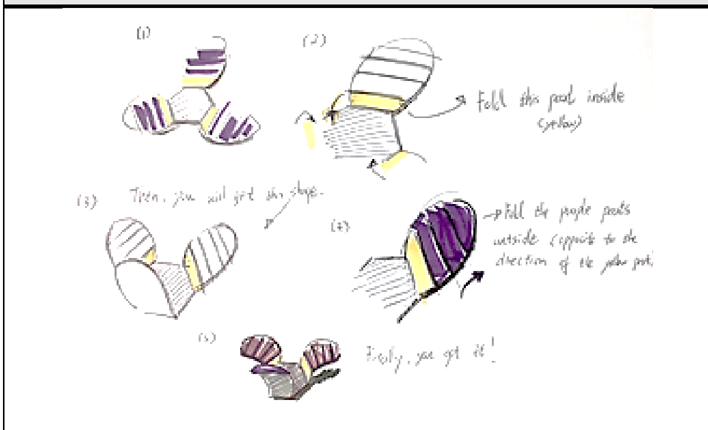
Group 1: Task 1 (4D Printing shape-change)	**Participants 1 and 2**
	Numbering for a step-by-step approach.
	Arrow to indicate direction and fold.
	Written notes with an indication arrow to point.

Figure 44. Focus group first task / Group 1 results

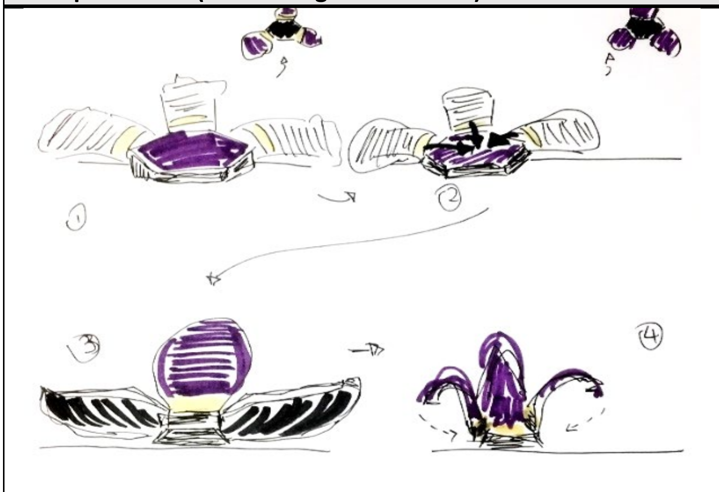
Group 2: Task 1 (4D Printing deformation)	**Participant 3 and 4**
	Numbering for step-by-step approach.
	No written words.
	Type of arrow: Dash line arrow Thick black arrow Long arrow
	Thumbnails to show two views (top and side).

Figure 45. Focus group first task / Group 2 results

Group 2: On the other hand, Figure 45 shows Participant 3 used a similar technique as Participant 1 by using numbering and arrows. However, additional thumbnail sketches were added to the primary sketches to indicate that the 3D object should be deformed from the flat surface. Furthermore, it also contained dashes, circular lines arrows to indicate object parts need to be folded. The feedback from Participant 4 is the sketches easy to understand even without additional description notes.

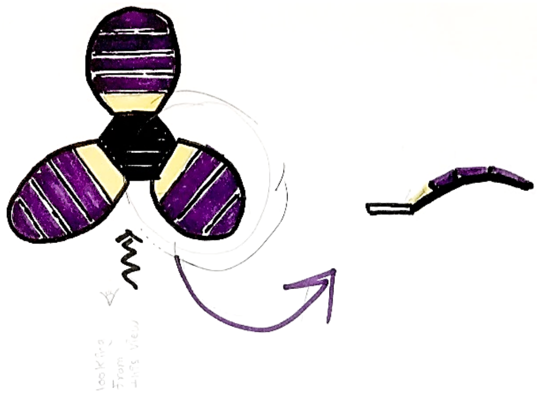
Group 3: Task 1 (4D Printing shape-change)	Participants 5 and 6
	Arrows used commonly Squiggle arrow
	Line weight for selection.
	Eye symbol for view angle.

Figure 46. Focus group first task / Group3 results

Group 3: During the first task, Participant 6 (receiver) expressed confusion with the direction of the mark on the paper, which was interpreted by Participant 5 (sender). This confusion may have arisen due to the small increments used in the sketches. To prevent this type of confusion, it is important to clearly understand and demonstrate the direction of shape-changing. Participant 5 included an 'eye symbol' under the squiggle arrow to represent the views angle from below the 3D object as shown in Figure 46. The argument between the sender and receiver happens when the receiver (engineer) misunderstands the 'eye symbol'. Usually, views from below or the underside angle point toward the top and are interpreted as worm's-eye views in engineer language.

Focus Group – Task 2

4.3.3.2 Result and Analysis for Task 2:

Results from Task 2, which analysed the finding from role-played to communicate 'timed sequence' through sketches, were discussed in the following figures:

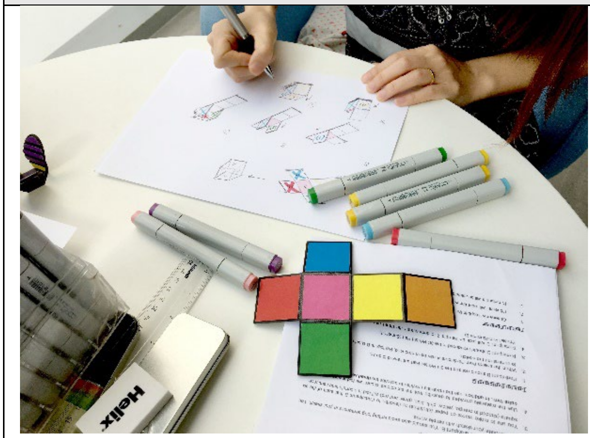
Task 2 - How to communicate 'timed sequence' in 4D Printing	
	
Designer as the ***sender***	Engineer as the ***receiver***

Figure 47. Tasks 2 – How to communicate 'timed sequence' in 4D Printing.

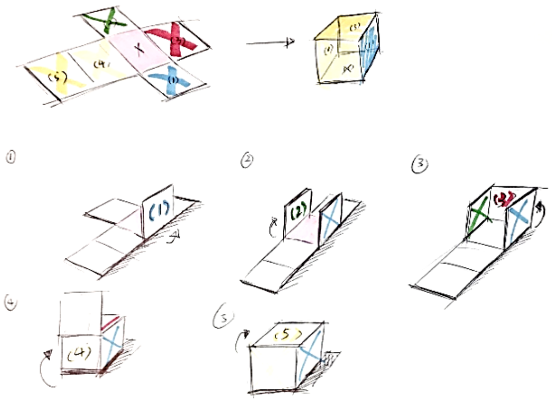
Group 1: Task 2 (4D Printing timed sequence)	Results
	Showed labelling of sides
	Showed step by step guide
	Used colour to represent sides
	Used number to indicate process
	Used arrows to indicate fold

Figure 48. Focus group second task / Group1 results

Group 1: In Figure 48 shows the sender indicated the timed sequence using an orderly number. The sender also labelled every side of the boxes with correspondent colours. Then, to ensure the receiver folded in the correct order, the sender combined numbers and colours to show step-by-step the sequential. The receiver manages to understand the instruction of the task clearly without hesitation. Furthermore, receiver feedback from the technique the sender used to communicate the timed sequence by using the mark on paper (arrows) makes the receiver easy and better to understand the instructions.

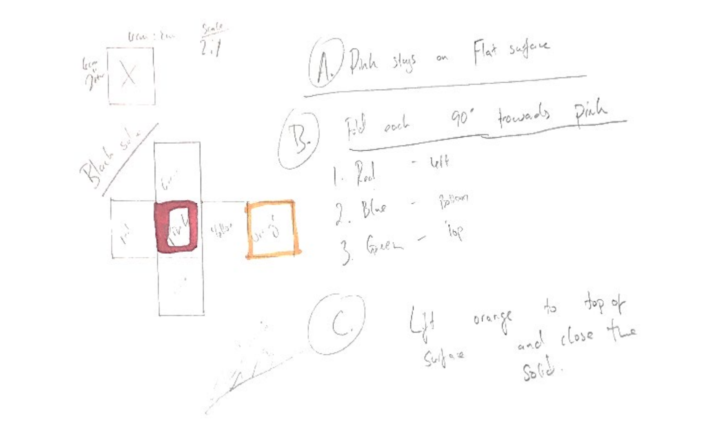
<table>
<tr><th>Group 2: Task 2 (4D Printing timed sequence)</th><th>Results</th></tr>
<tr><td rowspan="3">
</td><td>Explained every step using written words.</td></tr>
<tr><td>Not using any arrows.</td></tr>
<tr><td>Colour to indicate side.</td></tr>
</table>

Figure 49. Focus group second task / Group2 results

Group 2: In Figure 49, opposite Group 1, the sender in Group 2 used a technique in which the sketches only clearly defined the edges, resisting the temptation to colour in shadows. This leads to misinterpretation and makes it hard for the receiver to understand the instruction by the sender. In addition, the sender added some notes alongside the sketches to direct the receiver to follow the step-by-step timed-sequence process. The sender also used colour to indicate the side of the boxes; however, red is indicated in the wrong spot. The receiver struggled to follow the instructions but solved the task.

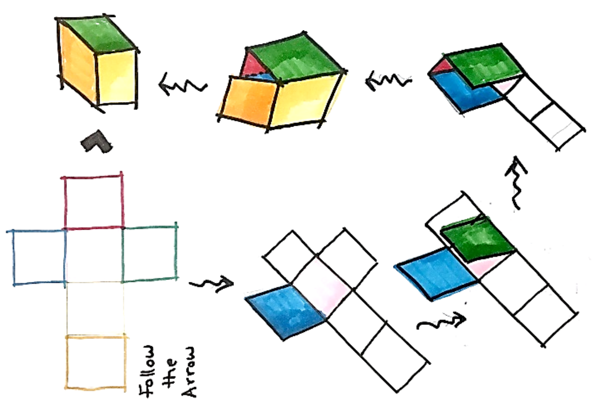
<table>
<tr><th>Group 3: Task 2 (4D Printing timed sequence)</th><th>Results</th></tr>
<tr><td rowspan="4">
</td><td>Two types of arrows
Bold shape arrow
Wiggly arrows</td></tr>
<tr><td>Colours to represent side.</td></tr>
<tr><td>Arrows to explain steps.</td></tr>
<tr><td>Write note to indicate start point.</td></tr>
</table>

Figure 50. Focus group second task / Group3 results.

Group 3:

Figure *50* shows how the sender in group 3 communicates the timed sequence. The sender used squiggle arrows to instruct the order to the receiver. In addition, the sender also used colours to indicate the side of the boxes and guided the receiver to follow the arrow point start of the process. The receiver understood the order and solved the tasks efficiently, even without any numbers to direct the process.

Focus Group - Task 3

Speed is the third elements in the 4D Printing elements; it has the dimensions of distance divided by time. This task is to find out how designers, as the sender, communicate to represent fast or slow speed through sketches in the 4D Printing design process. Task 3 is to communicate the speed shown in
Figure 51 using Object 3. The sender was asked to communicate with the receiver using sketches to deform the object given into a pyramid or triangle shape with speed.

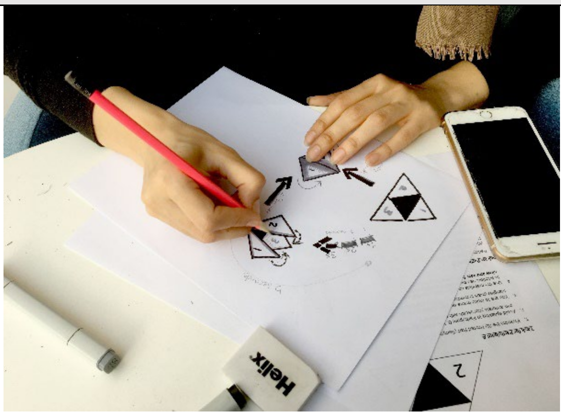
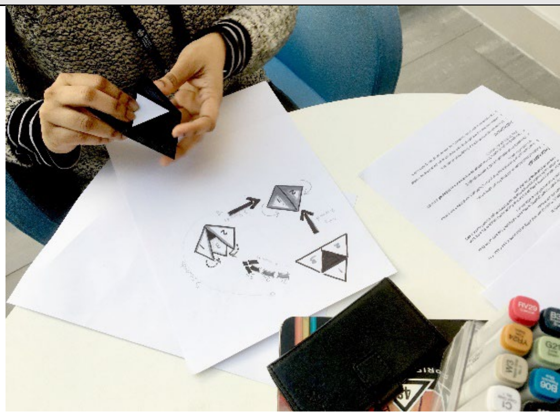
Task 3 - How to communicate 'speed' in 4D Printing	
	
Designer as the ***sender***	Engineer as the ***receiver***

Figure 51. Tasks 3 – How to communicate 'speed' in 4D Printing.

4.3.3.3 Result and Analysis for Task 3:

Results from Task 3, which analysed the finding from role-played to communicate 'speed' through sketches, were discussed:

Group 1: Figure 52 shows the sender used colours to differentiate the speed movement by representing *green* as the first phase, *red* as the second phase, which represents the beginning folding deformed and *blue* colour with shading to represent the final move to create the pyramid shape. The sender also represents speed time by using the symbol 's', and its base unit of measurement is the second. Aside from that, the sender added thumbnail sketches with notes and arrows as a detail part to assist the receiver in understanding the direction. The receiver can understand the sketches' direction made by the sender to solve the task.

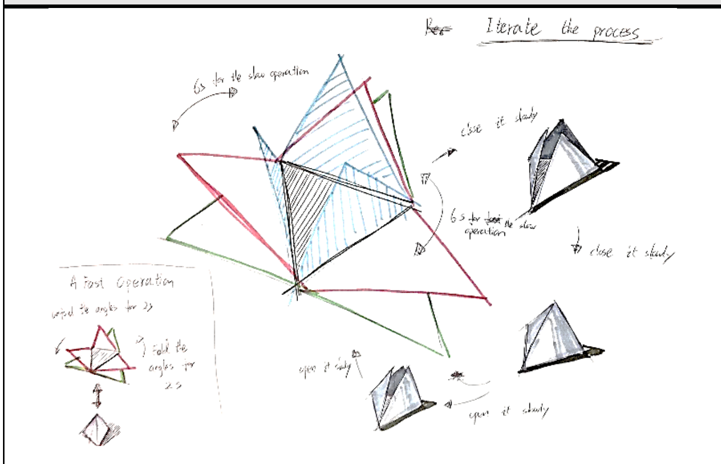
Group 1: Task 3 (4D Printing speed)	**Results**
	Shadings and colours to differentiate surfaces.
	Wrote ‘6s’ to represent slow speed.
	Wrote ‘2s’ to represent fast speed.
	She used lots of written words.

Figure 52. Focus group third task / Group 1 results.

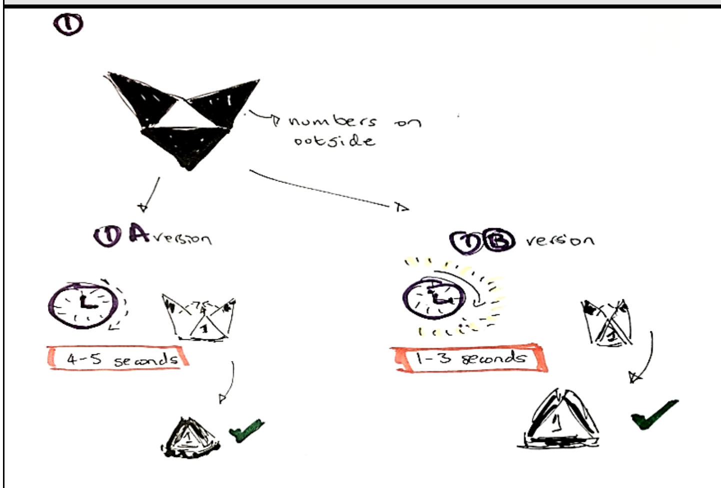
Group 2: Task 3 (4D Printing speed)	**Results**
	Wrote A and B versions.
	Highlighted speed in the red box.
	A timer symbol was used.
	The ticked symbol means the end of the finished process.

Figure 53. Focus group third task / Group 2 results.

Group 2: Figure 53 for participant 3 (Group 2), time was indicated using ‘symbols’ and splitting this into two separate sketches to define the differences in speed. A clock represents the cycle of time which indicates the speed of time for 4D Printing in this task. By separating time and noting the time below the clock symbol, the sender tries to keep the receiver grounded in the instruction. Similarly, the concept of denoting minutes used by Participant 5 is the same as participant 1.

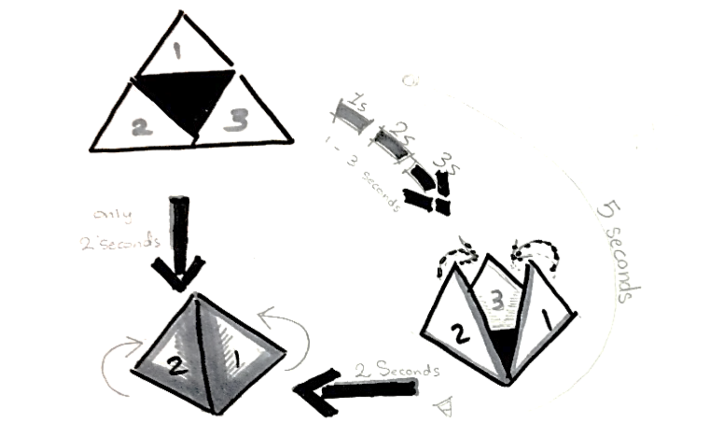
Group 3: Task 3 (4D Printing speed)	**Results**
	Only black and white was used.
	Dotted line arrow to indicated time speed.
	Used different types of arrows: -Bold arrows -Folding arrows -Arrows to represent process

Figure 54. Focus group third task / Group 3 results.

Group 3: In Figure 54 sender divided the sketches into three phases and then set out individual instructions for each section. Furthermore, the sender communicates the speed with three different types of arrows. The first arrow with bold and black colour is used to point at the final shape. Next, to represent the speed of seconds, participants used bold and dotted arrows by combining them with the numbers connected to the progression of time. The third arrows with circular and dashes represent each side of Object 3 that needs to be deformed at the same speed and time. However, the receiver was confused because the sketches only showed 'arrows' and 'colours but still managed to solve the task.

4.3.4 Discussion

The study concludes by recommending that sketches can be used as a methodological technique to help elicit meaningful responses from designers and engineers. Based on the sketches and tasks provided by the participants in the focus group 'role-played', the collected data from the focus group role-played was analysed and synthesized into key findings. This study has investigated the multiple layers of meaning-making designers and engineers created and communicated through sketching. The researcher experienced several benefits when using sketches as a methodological technique in the focus group sessions. The sketches helped the researcher gain insight into the designer and engineer's perspectives, provide structure and focus, and recognise the potential research.

Furthermore, this session contributed to the researcher's understanding of the richness of marks on paper to create the meaning-making process through a semiotic perspective. A marks is a graphic shape, such as a circle or square. Various marks are commonly used, such as geometric, abstract, and organic forms. Although a mark does not have a specific meaning, it can give a new significance to a concept or idea. For instance, combining multiple marks can create a new visual representation of a concept. Aside from being used as a visual representation of a concept or idea, marks can provide context or as ornaments in composition. One of the most important factors you should consider when using marks is the intended message. Doing so will help keep the viewer focused on the main point of the design.

The focus group role-played process influenced how participants communicated with each other in their responses, suggesting the value of analysing group processes in multicultural focus groups. In job shadowing, observation is an excellent elicitation technique that helps the researcher understand requirements based on observations related to the process flows of designing 4D Printing. Participants sketching featured unconventional signs, marks and symbolic resources to signify central ideas, whereas sketching was often a reflection of the 4D Printing elements. A key implication of this study, and what the researcher observed from participants' sketching, is the importance of sketching in designers' and engineers' constructions of their understandings of symbol interpretations.

Analysis of this focus group found that participants used marks on paper, such as arrows, colours, lines, etc., to communicate the 4D Printing elements. In this focus group, all visual variables of the mark or sign are part of the designed ‘symbol’ and can be controlled by the sender (designer). In addition, it is a thought or idea participants used as a word representative. Accordingly, symbols are potentially suitable for representing properties related to communicating. The remainder of this focus group session reviews various usages of the mark as part of literary symbol design. Each usage corresponds to a different semantic role. Furthermore, participants' sketching brings a schematic analytical lens, provides a further layer of meaning and offers deeper insights into participants' thinking forms than content analysis alone. The collected semantic roles are later classified in the quantitative data in (Section 4.5) and used as a foundation for the interpretation in the next chapter (see Section 5.4).

4.4 Observational Study (Iteration Three)

The literature review uncovered studies investigating possible interaction or communication between designers and engineers in communicating 4D Printing elements. Studying these interactions is fundamental to understanding designer and engineer information designing and processing decisions. As indicated in the research method (see Section 4.1), a semi-structured interview was conducted as the primary qualitative instrument in the first phase of the exploratory sequential design used in the mixed-methods study. To follow up the second phase of exploratory sequential mixed methods design results from the semi-structured interview and focus group served as the foundation for the quantitative phase in this observation session study. The purpose of exploratory mixed methods design is a process that involves gathering qualitative and quantitative data to explore a phenomenon of the study. It then uses the quantitative data to explain the relationship between the qualitative data and the findings [256].

The goal of the sequential design process was to facilitate qualitative exploration and quantitative follow-up. In this study, the researcher used quantitative data to design simulation scenarios. The effects of mixing quantitative and qualitative methods in the study resulted in a more substantial effect on the results—phase one focus group of this study to explore the existing representation to communicate 4D Printing shape-changes behaviour. The results from the focus group will be developed in the observation study; as the qualitative data (focus group) suggested that barrier responses are marks on paper or graphical symbols, the researcher decided that the observation study would be used to test the symbols.

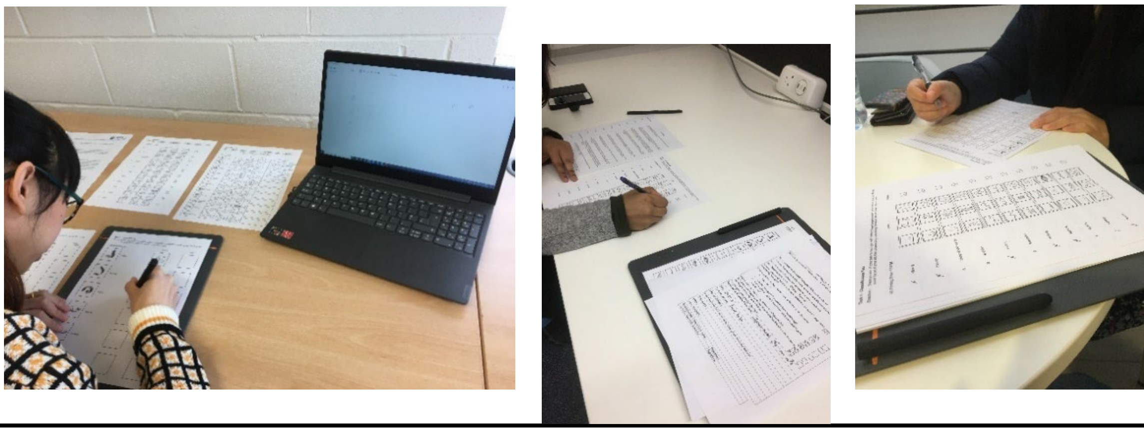
In data analysis from the focus group study (see Section 4.4), the researcher identified an existing process to represent communication for 4D Printing to be communicated during the early stages of the design process. Researchers found that participants made random marks or signs while communicating the 4D Printing elements. However, no recognised or standardised symbols were available to represent 4D Printing elements, especially for the shape-changing behaviours. This study used symbols to represent shape-changing behaviours to convey the core message's visual communication effortlessly. This observation describes the study in which the main objective was to evaluate whether established symbols could effectively communicate the shape-changes behaviour of 4D Printing. The main objective of this observational study was to design a usable symbol for shape-changing behaviour as a representation to communicate 4D Printing behaviour. The researcher used the participatory symbol design process, a procedural design alternative, for its effectiveness in generating 4D Printing communication based on task completion accuracy.

4.4.1 Participant Recruitment

Snowball sampling, a strategy in which the acquaintances of participants already recruited are approached and invited, was used to recruit participants in the second phase of this study [257]. It is also worth noticing the size of individual observation experiments can vary from 3 to 12 participants. A total of 14 participants (designer and engineer) were recruited to participate in this observational study. It was conducted in the Department of Design, College of Engineering, Design and Physical Sciences at Brunel University London in the United Kingdom and Faculty of Engineering, Universiti Teknikal Malaysia Melaka, Malaysia. In order to ensure that the participants had the required level of knowledge and skills, the researcher selected those who knew about 4D Printing technology and were familiar with the visual communication process. These measures were taken primarily to ensure that all participants have an implicit perception and understanding of 4D Printing. This study was conducted in line with the research ethics guidelines provided by Brunel Research Ethics Online (BREO). Informed consent was sought to receive endorsement before commencing the experiment research study. The ethical approval process aims to ensure research integrity and that the participant understands that the information given will be kept secure and confidential.

4.4.2 Procedures

Table 11. Participants were undertaking the observation tasks.



Task 1 - Classification Test Required participant to match set of symbols with the corresponding 4D Printing shape-changing behaviour.
Task 2 - Preference Test Required participants choose preferred symbols to represent the 4D Printing shape-change behaviour.
Task 3 - Development Test Required participants to generate two symbols of 4D Printing based on their idea.

Before starting the task, the observation procedure was adequately explained to participants; participants were briefed about the study's purpose and procedure. All participants received written information on the study and indicated their consent before proceeding with the interview. They were asked to read an information sheet before completing a consent form to participate in this study, in line with the university's ethical process. The participants were not timed and were given sufficient time to complete all the tasks. The average time each task lasted to complete the study was approximately an hour. The session for this study took place between 22 March 2019 to 30 March 2019.

Before data collection, notes related to the introduction of the 4D Printing eleven shape-changes behaviour were used to guide the participants in clarifying some essential points for answering the tasks. This study examines whether pictorial or graphical symbol influence and enhance the communication barrier in designing 4D Printing. The design of this study used the observation method. More specifically, the observation consisted of three main tasks: Task 1: Classification, Task 2: Visualisation and Task 3: Development, as shown in Table 11. Each task aimed to collect data on participants' perceptions and ideas related to their experiences regarding collaborative and reflective activities.

4.4.3 Data Analysis and Results

The data were collected through observation-based experiments/tasks. The data collection method is classified as a participatory study, where the researcher is immersed in the setting where her participants are while taking notes and recording simultaneously [258]. Researchers usually choose a question format that fits their needs when designing an activity or instrument while considering various practical constraints [259]. At the same time, observational methods may be characterized by their degree of formality, based on the structuring of the observations and recording methods and their intended use. Three tasks were identified and categorized into their similarities and priorities Table 11. The observation strategy consisted of assigning a set or group of symbols to each 4D Printing shape-changes behaviour. The data support a quantitative model in which participants approach each question with varying degrees of compression, which researcher label as classify, preference and development, rather than constant random guessing. This study tasks with varying levels of understanding and demonstrate that the format has a greater capacity to characterize participant thinking regarding the various response options.

Task 1 – Matching Test

This task examines the visual matching test designed in Task 1 - The matching Test help researcher develop a range of ideas to build the foundations for later concepts. The visual memory and discrimination involved and the identification of symbols or patterns, relationships, similarities and differences help the researcher learn about early representation and problem-solving. Although matching questions can be useful in assessing knowledge of terminology (matching the symbol with its definition). A 'Matching Test' in the first task asked participants to connect symbols from the list with the shape-change behaviours labelled on another.

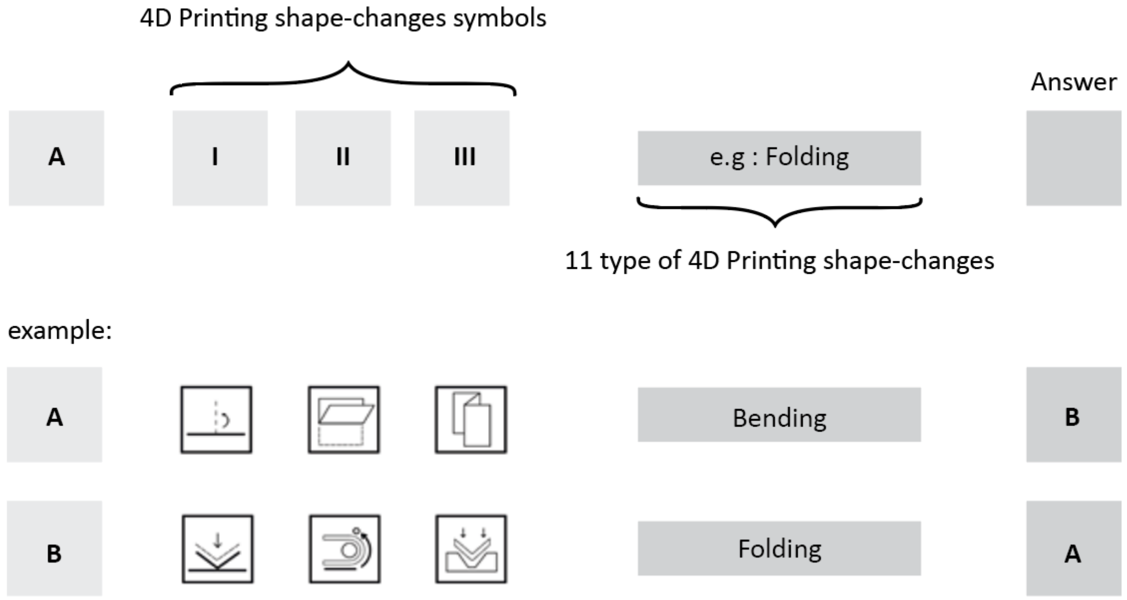


Figure 55. The layout of the procedure for Task 1 – Matching Test

Furthermore, this task introduces the eleven 4D Printing shape-changing behaviour to enable the participants to understand the 4D Printing shape-changing behaviour clearer. Furthermore, Task 1 was included with simple explanations of 4D Printing shape-changes behaviour meaning and was presented to the participants. The given direction for this task is participant need to match all symbols with the right 4D Printing shape-changing behaviours name provided. The researcher also emphasized that the questions in Task 1 were not designed to ask the participants to answer the questions with the exact correct answers. They were modified to make the participants feel more comfortable taking the task. The material to be matched consisted of 11 sets of initial design symbols to be paired with the presented form of 4D Printing shape-changes behaviours names. For data analysis and presentation, the response options have been reordered. The first set of symbols corresponds to the suitable 4D Printing shape-changes behaviour option, and the remaining incorrect or false options are ordered sequentially according to their behaviours. The suitable answer for fording is a symbol from label 'A', as shown in Figure 55.

The use of the Matching Test activity can provide a variety of advantages. The test allows the researcher to cover more content in a shorter time frame and provides an efficient testing method. Moreover, it also helped in the measurement of participants' knowledge. One of the main disadvantages of using matching test items is the tendency to focus on recalling information. This is because many adult learners tend to require practice in higher-order thinking skills. Instead of focusing on knowledge recall, try to develop other testing methods. For instance, the researcher tries to use this format to test the participants' reasoning skills by presenting a short scenario.

4.4.3.1 Result Analysis -Task 1

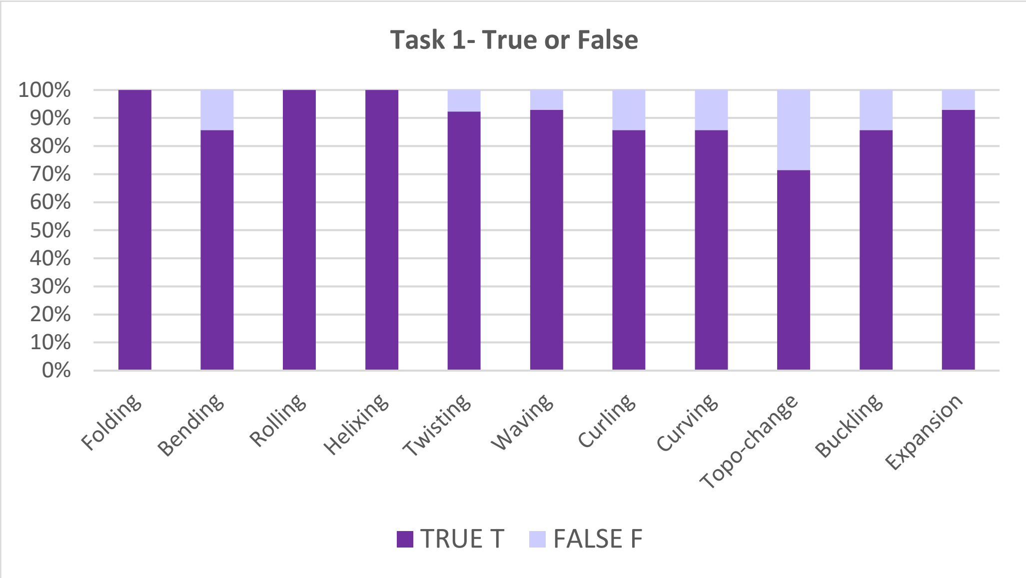


Figure 56. Results from Task 1 – Matching Test.

As mentioned, participants were asked to match the eleven shape-changes behaviour names that were suitable for the symbol set design provided. The correct matched and error rates were collected for the data analysed. The results of Task 1 - Matching Test are presented in Figure 56. The 'T' shown in Figure 56 referred to suitable or correct answers, and 'F' was used to represent the Wrong answers made by the participants. The result shows that 100% of participants received correct answers for 'folding'. The bending symbol with 86% corrects matched symbols and 14% wrong. 'Rolling' received 100% correct answers similar to 'helixing'. For 'twisting', 93% of participants answered correct and 7% with wrong. Next, 'waving' with 93% correct matched and only 7% with the wrong answer. 'Curling', 'curving', and 'buckling' with 86% same per cent matched correct answers and 14% wrong. 'Topographical change' received with 71% correct matched by participants with 29% wrong. The eleventh shape-changing behaviour, 'expansion and contraction', received a 93% correct match. The results concluded that most of the participants managed to match the representative symbols correctly.

Task 2 – Preference Test

Preferences tests are commonly used to measure the aesthetic appeal of a design. They can also be used to judge the quality of the design based on various factors, such as its trustworthiness and how well it communicates a specific idea. In addition, it involves asking participants a question about which image they would prefer and sowing the images. The goal of this ‘Preference Test’ is to determine which of the two or more alternatives a person chooses. This measure can determine if the choice is affective or behaviorally related. In the second task, the researcher used the ‘Preference Test’ for determining symbol design preference to identify the preferable or agreeable of the initial symbol design created based on the focus group study (see Section 4.4) to communicate 4D Printing shape-changes behaviours. This study was done by putting different goal boxes on the top of the symbols to help the researcher decide which symbol can be used in developing 4D Printing shape-changes behaviours and communication barriers. This type of testing can be done before a product is completed, which allows the researcher to get feedback early on and adjust it as needed. Qualitative and quantitative feedback allows the user to understand the main factors that affect a design's quality.

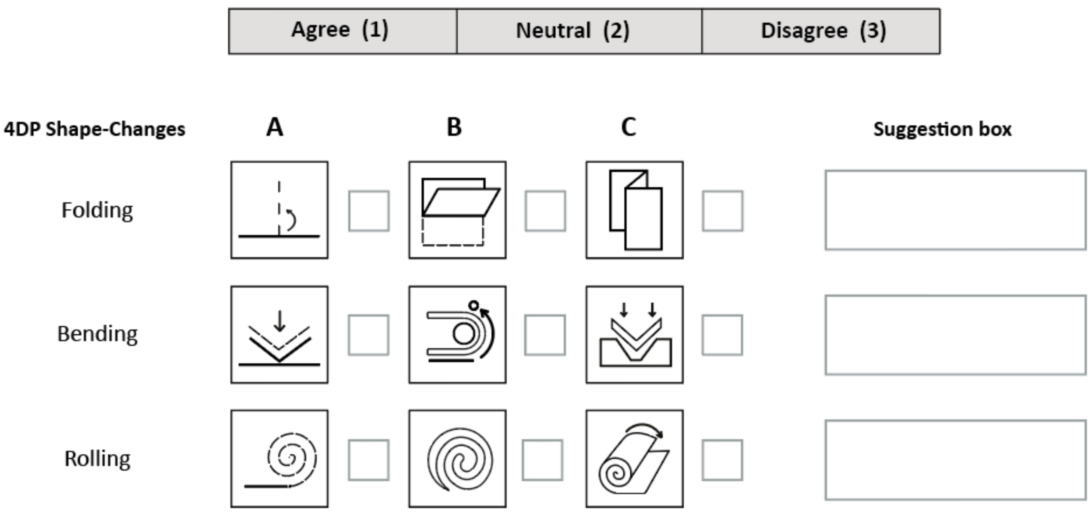
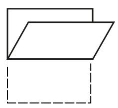
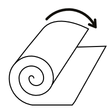
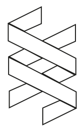
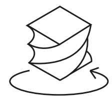
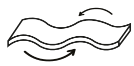
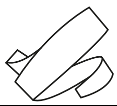
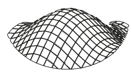
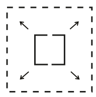


Figure 57. Illustration layout of visual design adapted for Task 2 – Preference Test

In the ‘Preference Test’, participants had to rate each of the three symbols according to to Agree, Neutral and Disagree, as shown in Figure 57. For this second task, the researcher aims to determine which symbol design is the best preference for the user/participants. Participants were asked to choose or compare the choices between three alternative initial symbol designs by identifying the most preferred symbol to be represented as the 4D Printing shape-changes behaviours. The preference scale is a point scale which it used to allow the participant to express how much they agree or disagree with the design symbols.

4.4.3.2 Result Analysis - Task 2

Table 12. Agree on symbols chosen by participants

11 shape-change behaviours					
					
Folding	Bending	Rolling	Helixing	Twisting	Waving
					
Curling	Curving	Topographical change	Buckling	Expansion	

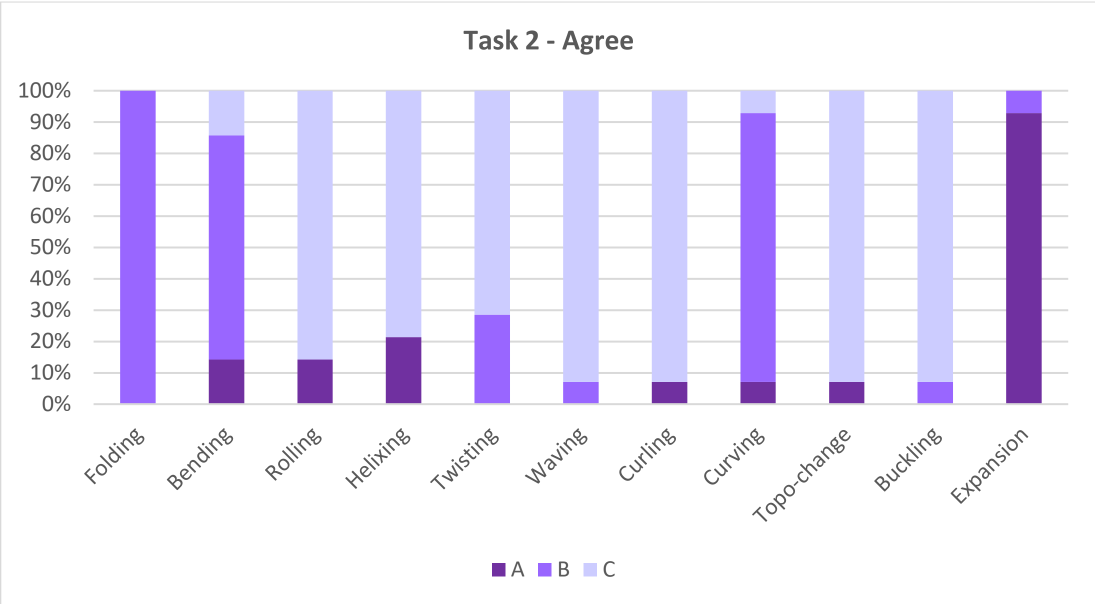


Figure 58. Results from Task 2 - Preference Test. (Agree)

Table 12 shows the eleven preferable symbol designs for 4D Printing shape-changes behaviours results from the Preference Test in Task 2. The result for the second task shows in Figure 58. The first symbol has 100% of the participants agreeing with the ‘B’ symbol to represent the ‘folding’ shape-changes behaviour for 4D Printing, which means all participants agreed with the symbols. The second symbol represents *‘bending’* 71% of participants agreed with ‘B’, 14% were neutral with ‘A’, and 14% disagreed with ‘C’. Regarding the third symbol to represent *‘rolling’*, the participant agreed ‘C’ symbol with 86% and chose 14% for ‘B’. The fourth symbol to represent *‘helixing’* has 79% agree with the symbol ‘C’ and ‘A’ as the second choice 21%. In the fifth symbol, ‘C’ has 71% agree to represent *‘twisting’*, ‘B’ and neutral with 29%. Of most participants, 93% agreed ‘C’ symbol represents *‘waving’ and ‘B’, and 7% with neutral.* Similar to ‘waving’, the symbol ‘C’ has 93% agreed to represent *‘curling’.* More than fifty percent of the participants agreed with the symbol ‘B’ to represent *‘curving’,* with 86%. Followed by ‘A’ with 7% neutral and disagreed with ‘C’ with 7%. The ninth symbol to represent *‘topographical change’* has 93% agreed with ‘C’ and neutral ‘A’ with 7%. In the tenth symbol, ‘C’ has 93% agreed to represent *‘buckling’ and ‘*B’ 7%. For the last symbol, 93% agreed with ‘B’ to represent *‘expansion and contraction’ and neutral ‘*B’ with 7%.

Task 3 – Idea Development Test

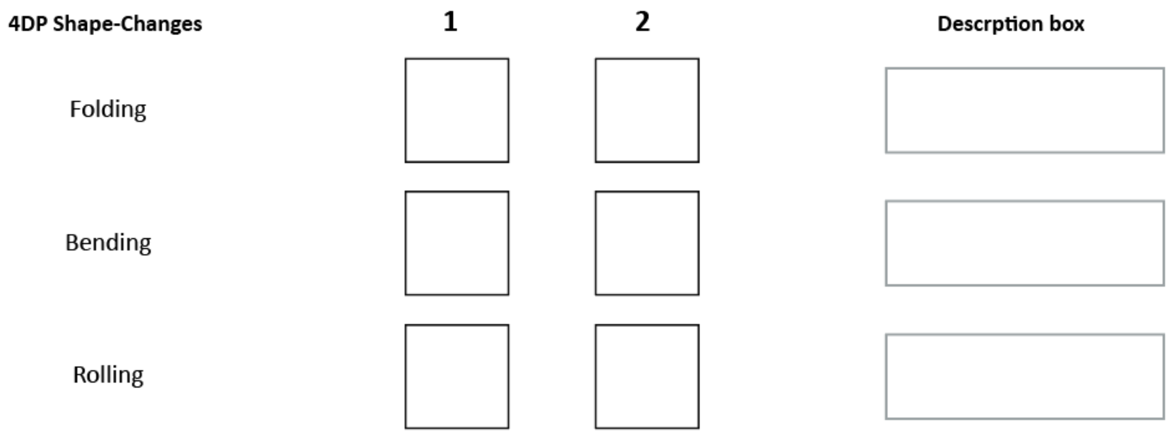


Figure 59. The layout of the procedure for Task 3 – Development

After the initial symbol designs were selected in Task 2, the third task was to explore the participant's degree of understandability. The tasks were carried out individually, and each participant was asked to provide their idea regarding a suitable symbol design to represent 4D Printing shape-changes behaviour. The idea generation process phase is a step in developing a prediction that serves as a basic estimate for construction phases. It involves identifying the main ideas and developing a more refined and articulated design concept. The third task, 'Idea Development Test', describes the idea generation process of developing the 4D Printing initial symbol. The purpose of this task was to allow participants in suggested and identified missing or incomplete requirements in Task 2. Figure 59 shows the illustration of Task 3 – Idea Development Task procedure, where participants were asked to create two alternative symbols designs to represent the 4D Printing shape-changes behaviour in order to deliver a full design development symbol set.

A brief task introduction was given to each participant, with the task explained by using the 3D images with the meaning for each 4D Printing shape-changes behaviour. Participants were provided with Wacom Bamboo Tablet and pen to save directly symbol designs created by the participant from paper to laptop. Participants were asked to view an animation that showed the 4D Printing shape-changes behaviour through the laptop screen provided to ensure participants understood the Task 3 procedure. These allowed participants to get an idea and understand how each 4D Printing shape-changes behaviour deformed their shape in each specific way. Next, participants were asked to add an annotation to specify the marks or geometric relations using symbols, dimensions, angle, alignment and symmetry on their sketches to communicate the 4D Printing shape-changes behaviour. The study used OBS Studio Software to record participants' activity.

4.4.3.3 Result Analysis – Task 3

Table 13. Results from Task 3 - Development Test.

4DP shape-change behaviour	Similarity symbols created by participants
Folding	1. Arrow to indicate direction and folding sequence.
	2. Symbol for view angle.
	3. Dash line to indicate the axis of folding.
	4. Preferred 1D or 2D shape to indicate folding symbol.
Bending	1. Symbol 'F' to indicate force.
	2. 'G' indicate as Gear in the bending machine.
	3. More than one arrow to indicate the direction
Rolling	1. Curve arrows to indicate roll direction
	2. 3D shape to represent rolling shape.
	3. Rolling dash line.
	1. Used double line to indicate helix shape.

Helixing	2. Cross line and dash line.
	3. Curve arrows to indicate movement.
Twisting	1. Arrows circle around the symbol to indicate a twist
	2. 3D shape to represent twisting.
	3. Curve up and down arrows to indicate twist movement.
Waving	1. Wiggly lines represent wavy shapes.
	2. Shadings to differentiate changes shape.
	3. Arrows to indicate wave movement.
Curling	1. Single curling line.
	2. Thick curl line represents a 3D curl shape.
	3. Arrows to indicate curling movement.
Curving	1. Show two views representing shape changes.
	2. Dash semi-curve line above straight line to indicate curving shape.
	3. Semi-curve 3D shape.
Topographical change	1. Some of the participants indicate different movements with colour.
	2. Shading differentiates different surface
	3. Dash lines differentiate different surfaces and movements.
Buckling	1. Two arrows facing each other indicate force.
	2. 'F' symbol to indicate force.
	3. Sharp edge to indicate high compressive stress.
Expansions	1. Four or more arrows in every corner.
	2. Two different sizes of box to indicate expansion.
	3. Different sizes of the circle to indicate changes in size.

To better understand the participants' ideas of the suggested design symbols, the researcher first observed the participant's design symbols without interacting with them and did not interrupt them. Each participant participated in the study and created two design symbols for each of eleven 4D Printing shape-changes behaviours, which generated a total of 308 symbols design were created. There was no restriction on the number of strokes, orientation, or sketching style used to represent the 4D Printing shape-changing behaviour for this task. However, the symbols had to be drawn in black and white and sketched within the provided boxes. This ensured consistency across all participants, and the space given within the box ensured that the symbols created could be seen when shown within a tight constraint.

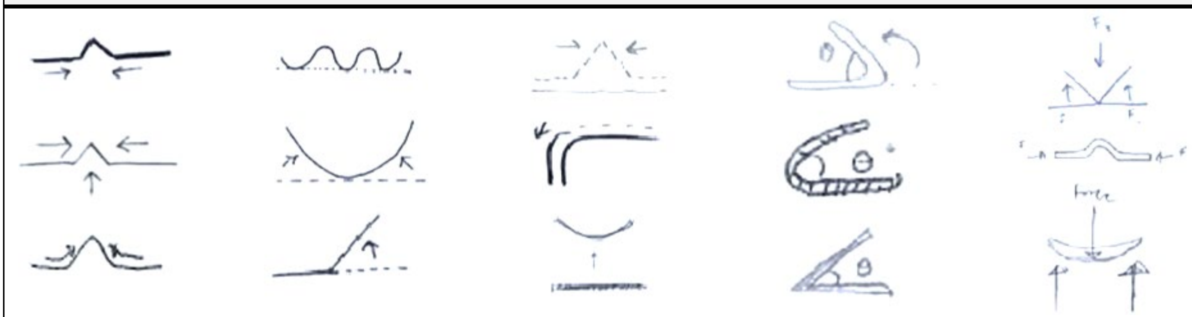
The results indicated significant similarities among participants with engineering backgrounds, where they usually included a known symbol that represented the angle, force, etc. Conversely, the most designer only used arrows and shading to define the features, especially in the 'topographical change' shape-changes behaviours. In order to thoroughly analysed the 308 symbols generated, the researcher observed and scrutinized every single symbol and made distinct observations for each symbol that has been summarized.

In Task 3, results showed significant similarities of annotation or mark in providing the idea development for the 4D Printing shape-changes behaviours representation symbols. Participants suggested similar representations for the specified 4D Printing shape-change behaviours symbols. The following findings outline the benefits of idea generation symbols versus evaluation symbols for communicating 4D Printing shape-changes behaviours. While discussing the task, some participants said they enjoyed suggesting designs and expected the participatory process would result in a better design.

4.4.4 Discussions

Table 14.The comparison between Task 2 and Task 3.

Some design representation 'symbols' proposed by researchers indicate 4D Printing shape-changes behaviour.

Task 2 - The highest agreements were received for any symbol in 3D shape and did not show any angles and arrows.

Task 3 – Symbol designs from the 4D Printing shape-changes behaviours personnel sketches. Most participants used arrows, angles, and lines either in 1D or 2D shapes to indicate 4D Printing shape-changes behaviour.

Based on the observations study, there is an inconsistent result between the preferred symbols in Task 2 and Idea Development Task 3, as shown in Table 14. In Task 2 and Task 3, there are mismatches or differences between the participant's symbol drawing (see Section

4.4.3 in Task 3) and preference (see Section 4.4.3 in Task 2) symbols proposed by the participants to represent 4D Printing shape-change behaviours.

For example, most participants used arrows, angles and sequences of folding either in 1D or 2D shape to indicate the folding symbol as presented in Task 3. However, results from Task 2 were received in 3D shapes and did not show any angles or arrows, as shown in Table 14. Therefore, from this observation, the researcher concluded that it is easier for the participants to communicate and understand a 2D shape symbol, including arrows and angles, to represent a shape-change behaviour of 4D Printing.

4.4.5 Validity

One of the research objectives is to examine and classify the communication elements between designers and engineers when designing 4D Printed parts. Therefore, the first focus group answered this question, where the marks on paper, such as using an arrow, dotted line, etc., indicated by participants for each word was or were appointed as a symbol representing that word. It was seen that the participants tried to express or communicate words included in the form by marking on paper to describe the elements of 4D Printing. Therefore, research results suggested that designers and engineers consider communication tools when applying 4D Printing to the product. The design toolkit features elements representing various contexts related to shape-change behaviour, stimuli, and speed.

There are many aspects in preparing the study to conduct qualitative research. Among the consideration is to understand and articulate assumptions that guide the research. An underlying assumption in the leadership study is that reality is subjective, that people do not experience the world identically. Because of this assumption, the researcher chose qualitative methods to see individual perspectives and look for patterns among those sketches. Another important aspect is the trustworthiness of the findings in the study and the conclusions the researcher portrays. This study is frequently referred to as validity. Although, like other concepts in qualitative research, the concept has multiple meanings and interpretations. Denzin and Lincoln state validity determines whether a study investigates the phenomena intended to be investigated topic [251]. They assert validity is a function of the 'quality of craftmanship in an investigation and involves an iterative process of checking, questioning, and theoretically interpreting the findings.

4.5 Chapter Summary

The research in this chapter suggested that using conventional sketches to communicate 4D Printing does not fully convey the design intent. This paper provides evidence of poor communication between designers and engineers when describing 4D Printed parts. As mentioned in the Research Clarification (RC), the literature review highlighted that no studies had been conducted to investigate the communication barriers of the 4D Printing shape-changes design process. In summary, the study found that the marks made on paper in the Descriptive Study I (DS-I) used in Chapter 4 were spontaneous and unpredictable. For example, participants used random lines, arrows and other features to represent the 4D Printing shape-changes behaviour design process. Time was indicated by using 'symbols' and splitting this into two separate sketches to define the differences in speed. This Descriptive Study I (DS-I) have found that a conceptual framework could be further developed as a guideline to communicate the shape-changes behaviour of the 4D Printing design process. The main contribution to knowledge is to enable designers and engineers to communicate using 4D Printing during the idea generation phase.
Sketches are a powerful tool that allows designers to develop various ideas quickly and iterate through many design alternatives. Although a few studies have explored communication, participants applied design features on their sketches to communicate 4D Printing in the design study process. No standardised methods are available to communicate the shape-changes behaviour of 4D Printing. Designing a symbol is a time-consuming process with many different phases of development required to produce a powerful final visual representation. It is a collaborative process during which communication between the researcher and users is imperative. These DS-I studies have found that using pictorial symbols to represent 4D Printing shape-change behaviours could help designers and engineers apply standardised representations to communicate with each other during the design stage.

Furthermore, users tend to sketch symbols to communicate effectively with each other. In terms of making symbols more interactive, computers could be capable of understanding the meanings of the sketches. One of the elements of the most common symbol used in sketching is the arrow symbol. However, some symbols may be similar or identical to others but have different meanings. Due to its versatile nature, it is still challenging for computers to distinguish its semantic roles. A well-designed symbol can help people understand complex mental structures and mental shapes, which are often hard to communicate verbally. A computer capable of understanding these symbols could allow designers and engineers to efficiently carry out their work by sketching to explain their ideas and knowledge in developing 4D Printing processes and technologies.

Chapter 5:

DEVELOPMENT OF THE 4D PRINTING TOOLKIT

(PRESCRIPTIVE STUDY)

Chapter 5

DEVELOPMENT OF 4D PRINTING COMMUNICATION TOOL

Chapter content

Chapter Five states the main theoretical contribution of this research. It describes each phase and the findings of the 4D Printing communication applied using theoretical knowledge gained from the first research phase. The research outline illustrates the 4D Printing symbol's potential to address specific communication implementation barriers in 4D Printing. Also, it enhances communication between designers and engineers in developing and designing 4D objects.

5.1 Introduction

In this chapter five, the researcher focuses on the third stage of Design Research Methodology (DRM), the Prescriptive Study (PS) stage. After collecting and discussing the results of Descriptive Study I (DS-I), the study begins with developing design support. The prescriptive study is where methods and tools to solve the identified problem in DS-I are developed using experience and assumptions. This section includes a guideline, tools, methods, etc. In addition, the researcher reduced or eliminated the influence of other critical factors found in Descriptive Study I. In this research, the development of the symbol from chapter 4 results will indicate the design consideration for a communication tool for 4D Printing. Each symbol will represent a different type of element that the designer and engineer must be aware of. However, before finalising the symbol design, they should have a standard design concept to all look uniform and standardised.

Two online surveys were developed in this Chapter 5 to evaluate the result. This chapter structured the online surveys as follows. The first online survey is responsible for evaluating the finding from Chapter 4 through the process development of the 4D Printing communication toolkit in Section 5.2. The results led to validating the toolkit (symbols) for recognition and usability to the users, especially designers and engineers. This section supports the overall aim of this chapter which is to develop a series of design toolkits based on concepts from theories from the literature review that will help designers and engineers communicate in the design process of 4D Printing products. This development of new 4D Printing design symbols was designed to eliminate language barriers to achieve better delivery so that designers and engineers can communicate their intended ideas and messages effectively.

5.2 Online Survey I – (Iteration Four)

The purpose of using an online survey for this study is to collect the quantitative data as stated in the Design Research Methodology phase two (see Section 4.1.). This study used an online survey inquiry, which is the most efficient for collecting quantitative data [260]. Data from the previous study (see Section 4.4.7) were collected and analysed. Then, the researcher gathered all the information and results from the data by further redesigning the sketched symbols using Adobe Illustrator software to simplify and standardise the initial design symbols based on the participant's ideas and suggestions. One of the most important elements of a good symbol is consistency. To standardise the symbol visualization and characteristic, each symbol of the shape changes behaviour was generated with a consistent straight solid in black colour, this to represent 4D Printing part which in static mode (before morph). Second, to show the deformation which the characteristic or behaviour of each symbol, a grey dotted line emerged together with the solid line. In addition, all symbols created with a white background were produced using Adobe Illustrator and saved in the native file format for reproducibility. In this study, the researcher focused on the elements of design consideration for the communication tool to communicate ideas and illustrate visually to convey information rapidly and effectively. A step further, an online survey involving designers and engineers was conducted to evaluate the preference for 4D Printing design symbols.

5.2.1 Participants Recruitment

The online survey was distributed to designers and engineers through emails to existing contacts and contacts identified through Internet searches of designers and engineers. The email invitation contains the survey web link. It was also advertised online using relevant groups such as Brunel Postgraduate Group *cedps-pgr-students@brunel.ac.uk*. The sample consisted of a total of 116 '*one hundred and sixteen'* participants involved in this study. Participation was voluntary and was recruited through the snowball sampling method. Participants could take part from anywhere, although the survey was conducted in English. The survey was conducted anonymously to limit the social desirability response bias and to ensure that the respondents' nationalities and geographic locations were not recorded. The survey was conducted by asking the participants if they were a design or had an engineering background to ensure that the results were accurate. Participants were also asked to provide their informed consent. However, if the individuals did not consent or identify as a designer or engineer, they were excluded from the study. The Brunel Ethical organization fully approved the online survey (BREO) was informed consent before engagement in the study.

5.2.2 Procedure

An anonymous online survey was conducted from the 27th of October 2020 to the 16th of November 2020. The online survey consisted of two parts plus an additional form for participant feedback. The survey instrument was a sixteen-question online page developed for this study. Two variables contribute to symbol usability to communicate 4D Printing: shape changes behaviour, and type of stimuli. On each online survey page, one set of three variant options is displayed on the screen, categorized as Option 1, Option 2, and Option 3. The options set represent two 4D Printing symbol element: the 11 shape changes behaviour and the five types of stimuli, as shown in Figure 60. Most of the designs of the symbols were modified and redesigned by the researcher based on suggestions given by the participants from the previous method (see Section 4.47) before being used in this online survey. Part 1 required participants to select the shape changes behaviour symbol. For Part 2, the participants were asked to select the type of stimuli symbol. On the first page of the online survey, participants were introduced to the study's background and objective of the study. Then, participants provided their consent information before starting the online survey by ticking all the consents box. Next, the participant was presented with the three new 4D Printing symbol designs for each shape-change behaviour and stimuli were presented to the participant. The online survey lasted approximately 5 minutes.

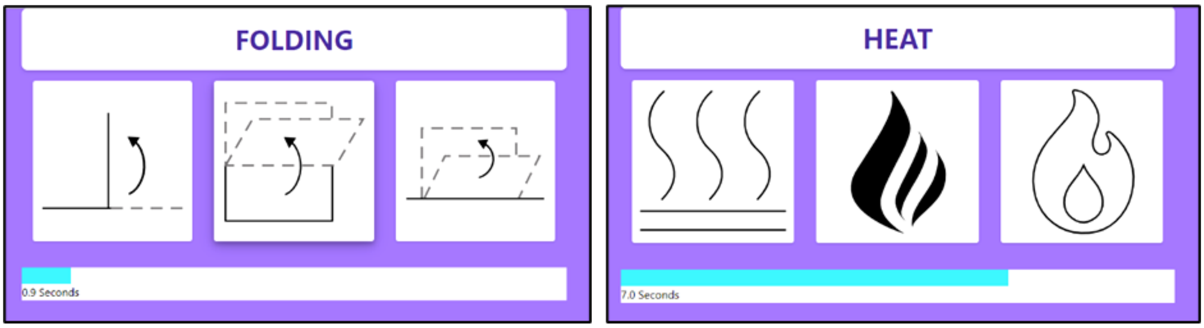


Figure 60. Overview of the shape change behaviour and stimuli symbol variants.

The main task of the online survey was to find a target symbol and select the target as fast as possible by selecting the most preferred symbol. This task also examined the speed of recognition through how long participants selected the visual of these symbols with their related labels. In order to ensure each of the participants got the same opportunity to respond, the survey displayed the time limit bar with *10 seconds* by starting counting from 0 seconds to 10 seconds, as shown in Figure 60. Participants were asked to select the best design to represent the 4D Printing shape-changes and type of stimuli.

As mentioned in the survey, participants were given a set time limit (10 seconds) to toggle the symbol design. The researcher created a *time limit bar* on the online survey to track and collect the data on the time a participant spends choosing their preferred represent symbol design. Furthermore, *auto-advance* was used in this online survey to replace the submit option button. An auto-advanced after (10 seconds) will automatically move participants to the next question page, even if participants have not selected any answers. The online survey consisted of 20 pages, including the consent page on the first page and the introduction pages for shape-changes and stimuli.

5.2.3 Data Analysis and Results

5.2.3.1 Results – Shape Changing Behaviour

This study utilised statistical analysis with a bar graph by categories on the x-axis and numbers on the y-axis. This analysis method allows the researcher to compare numbers (total of the participants) between different categories (shape-changes behaviour/type of stimuli). In this study, the researcher categorises the raw data into categories and visualises them. The categories in this study are independent; that is, changes in one of them do not affect the others. To summarise the data, the researcher used a table and bar chart/graph to present every data point in order. Data were collected via the online survey between 16 November 2020 and 20th November 2020. The data were analysed using Microsoft Excel 2016 software.

Two sets of questions have been asked of all participants. Each set is presented in its bar chart: shape-changes behaviour and type of stimuli. This study is intended to compare the percentage of the preference symbol design. The researcher is more interested in knowing which symbol design is the most preferable for participants. One hundred sixteen participants completed the online survey, and only completed responses were included in the data analysis. The majority of participants were designers (50%) and engineers (50%). Again, each shape-change behaviour was displayed for 10 seconds in three variant styles, and the process was repeated for each proposed symbol.

The bar chart in Figure 61 shows the results from phase 1 task – shape changes behaviour in this online survey I. The graph uses three sets of data (Option 1, Option 2 and Option 3) and is grouped into eleven categories (11 shape changes behaviour). The results indicated that half of the participants, 54% chose *Option 3* as the new symbol to represent *Folding.* For the second symbol to represent *Bending*, the majority of the participants preferred *Option 3*, 51%. The third symbol was *Rolling* with 38% *Option 1*; however, Option 3 with 34% became the participants' second preferred symbol. For *Helixing,* it is higher than half of the participants with a large percentage of 71% as *Option 3*. The preferred symbol to represent *Twisting* is *Option 2* with 42%. Following the next symbol, Option 1 became the preferable symbol selected by the participants, with 65% representing Waving. Participants selected the *Option 3* symbol to represent *Curling* with 51%. Next, 46% of participants preferred the symbol on *Option 3* to represent *Curving*. *Option 1* is the most preferred symbol representing topographical change, with 74% of the participants. Most participants have a similar preference for the Buckling symbol, with *74%* for *Option 1*. And the eleventh symbol with 56% of the participants preferred *Option 3* to represent Expansion.

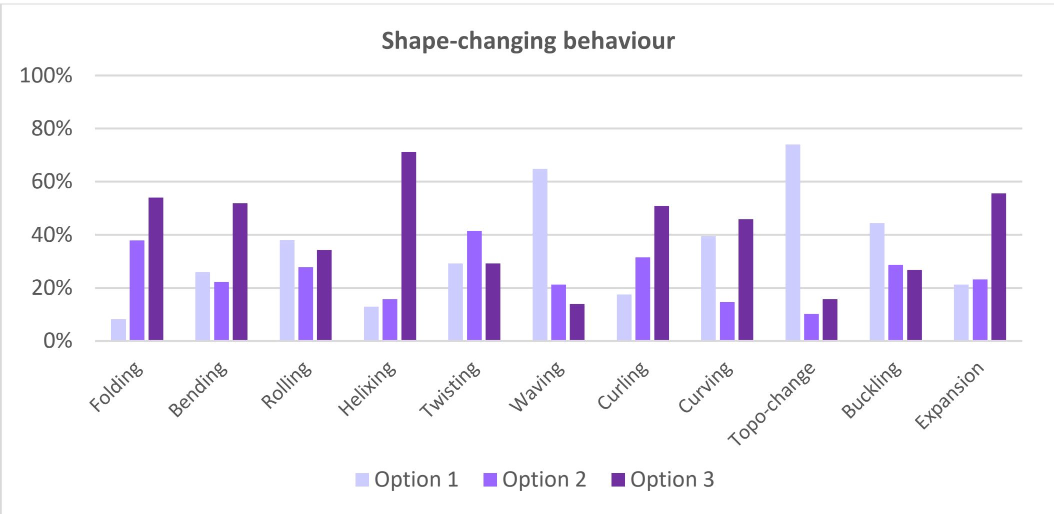


Figure 61. Results from the survey involved 11 shape-changes behaviours.

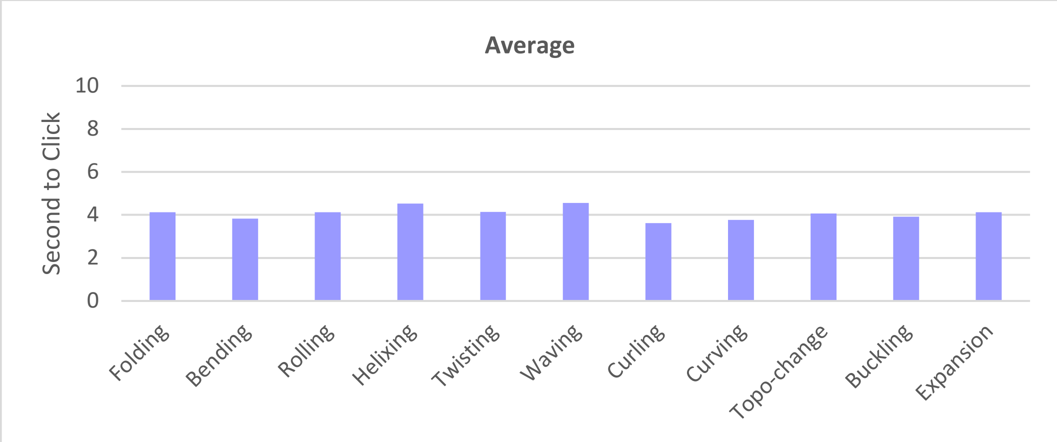


Figure 62. Average results timing click count for shape-changes

Figure 62 shows the average time participants spent selecting each 4D Printing shape-changes behaviour in the online survey. The average is the sum of the individual data point's speed of selection time divided by the number of points in the set (10 seconds). The average time for the 11 shape changes behaviour is 4 seconds, except for helix and waving, which took longer for participants with 5 seconds average time to select the preferred symbol.

Table 15. Results from the online survey indicate 4D Printing 11 shape-changes behaviours.

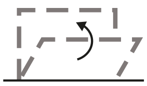
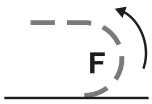
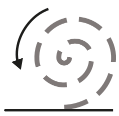
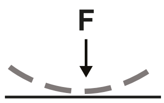
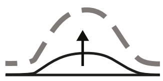
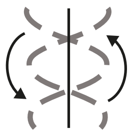
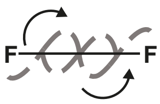
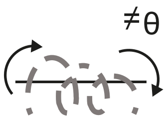
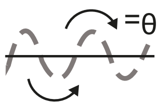
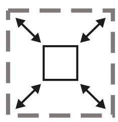
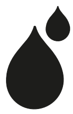
11 Shape-Changing Behaviour					
					
Folding	Bending	Rolling	Curving	Topographical change	
					
Helixing	Curling	Waving	Buckling	Expansion/Contraction	Twisting

Table 15 illustrates the preferred symbol for shape-change symbols behaviours of 4D Printing selected by most participants through this online survey. This results of 4D Printing shape changes behaviour symbol set is the final design to represent the communication tool. The final design symbols will then be used to communicate the 4D Printing design process in the second survey for the evaluation stage in the next chapter.

5.2.3.2 Results – Type of Stimuli

Table 16. Results from the survey indicate a 4D Printing type of stimuli.

5 Types of Stimuli				
				
Heat	Water	Magnet Field	pH Level	UV Light

For the second part of this study, similar to shape changes behaviour, type of stimuli were also provided with three variant options and 10 seconds timing bar. Participants were asked to choose which symbol option is the most preferred and the most suitable symbol to represent as the 4D Printing Stimuli. The five types of stimuli, including heat, water, UV light, magnetic field and pH level (see Section 2.3.4), were evaluated in this study. Each symbol was generated with a variant characteristic and a white background produced by the researcher using Adobe Illustrator and saved in the native file format for reproducibility to ensure the proposed design representation symbol is consistent. Table 16 presents the most preferred symbol for representing the type of stimuli of 4D Printing selected by most participants through this online survey. This results in a 4D Printing type of stimuli symbol set also is the final design to represent the communication tool. The symbols also then are used to communicate the 4D Printing design process in the second survey for the evaluation stage to evaluate and validate the applications that presented in the next chapter

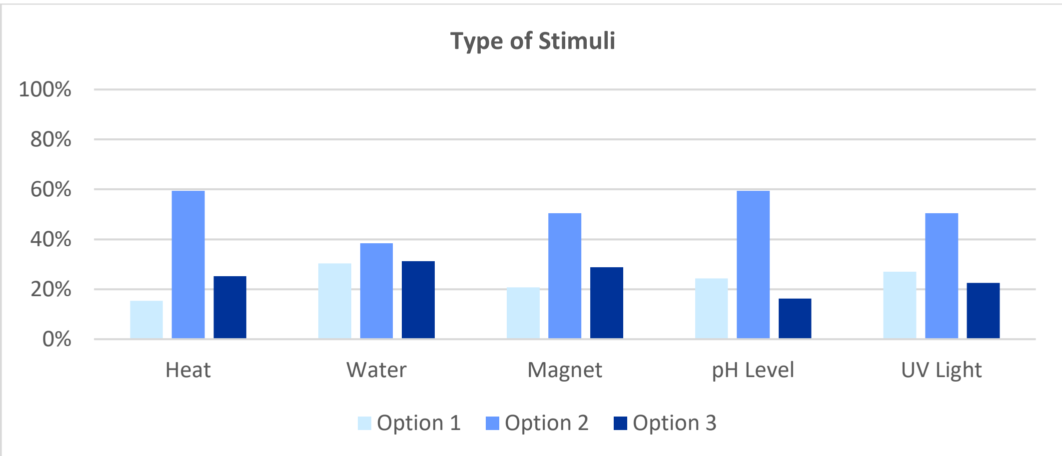


Figure 63. Results from the survey involving stimuli.

The analysis was carried out by presenting the results with a bar chart, as shown in Figure 63, with most participants preferring symbols in *Option 2*. Figure 63 Results show that the highest number of participants, with 59%, preferred the *Option 2* symbol style to represent 4D Printing stimuli for *Heat*. Regarding a symbol representing Water, Option 2 was also selected by the majority, with 38%. For the magnet field, 50% of participants preferred the second option. To indicate the communication symbol for *pH level*, participants preferred Option 2 with 59%. The participant selected Option 2 with 50% for the fifth symbol representing UV light. The researcher looked at similar results from this task where the symbols in Option 2 have the same style. This result may be led participants to assume the darker symbol is much stronger in preference among the other two options. This factor might be the reason for the perception of the symbol design, which affects the visibility of the symbol's visual display.

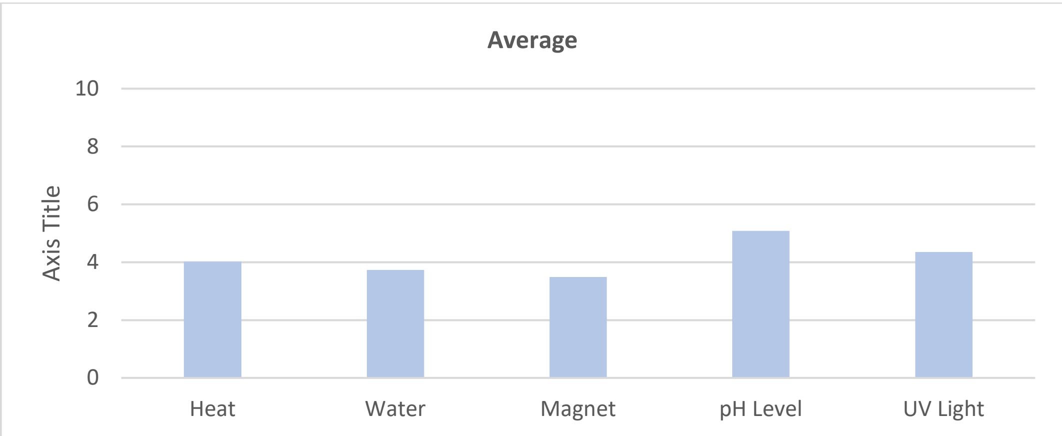


Figure 64. Average results timing click count for stimuli

The second phase of this study also provided the average time participants spent selecting each of the 4D Printing types of stimuli. The average selection time for this study is illustrated using a graph chart in Figure 64. The average time for the type of stimuli is 4 seconds, except for pH level, which took longer for participants with 5 seconds average time to select the preferred symbol. Overall, most participants who participated in this online survey showed positive feedback on their preference for the symbol visualisation, which is the symbol in Option 2. However, symbol effectiveness will be evaluated from the viewpoints of visual recognition and conceptual meaningfulness in the next iteration (see Section 5.3).

5.3 Online Survey II (Iteration Five)

In this second online survey, the researcher aims to evaluate the recognition and usability of the final design of the 4D Printing communication tool and whether the designers and engineers use the new symbols effectively to communicate the 4D Printing design process. During this limited testing evaluation, the objective was to uncover the recognition of the toolkit to communicate in designing 4D Printing. Moreover, visual accessibility and symbol recognition was included as characteristic being investigated in this study. The reason for this is that the previous research (see Section 5.2) has shown that both visual and recognition are related to symbol meaning and consideration. Accuracy of identification and symbol design is not only for the pursuit of its visual looks, but it has to ensure the recognition of the symbol and understanding of what these symbols mean to users correctly, quickly and effectively.

The purpose of technical drawing in this study is to examine the usability of the proposed symbol to be implemented as a communication tool. Technical drawing will be the interactive tool to determine the inspection methodology, how the designer and engineer will clamp the part down using the proposed 4D Printing symbol as a communication tool and what features have to be held concerning which [261]. The technical drawing can dictate the entire inspection process. Verifying the validity of design theory is based on the principles of logical verification and verified by acceptance. Validation in this study is concerned with establishing the relevance and meaningfulness of guidelines, methods, and tools. Validity is the degree to which a test examines what it is supposed to measure; it can include predictions [262].

5.3.1 Participants Recruitment

This second online survey was distributed to 65 participants, and 50 replied to participate in this study (25 designers' and 25 engineers' backgrounds). The study was conducted in the United Kingdom. The survey was sent out through social media and email and conducted using snowball sampling. All participants were informed about the study before they participated through the email invitation. Informed consent was obtained from all participants before participating in the study. Participants were also informed that the survey was anonymous. The link to the survey was included in the initial invitation email letter.

Participants were contacted by email and invited to complete an anonymous online survey (approximately 5 minutes) via http/. Inclusion criteria for the participants are they need an engineer or designer background to provide feedback on the questionnaire answers.

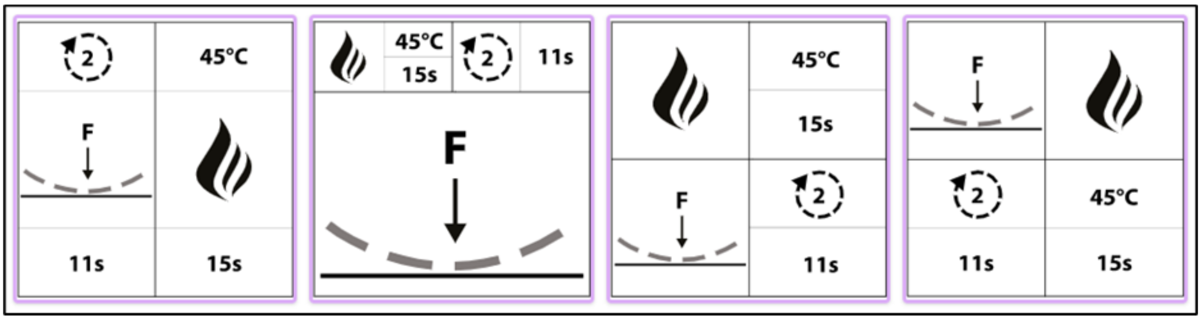
5.3.2 Study Procedures

In this study, the online survey was carried out in three steps identified as Phase 1, Phase 2 and Phase 3. This second online survey did not include the timing bar to ensure participants understood the task and had enough time to complete the survey. Participants took part in the study via a web link provided by the researcher that navigated them to an online survey webpage. Designers and engineers from different backgrounds tested the symbols' design. Before beginning the survey, participants were asked to read and agree to an informed consent form. The experiment was divided into three parts: elemental arrangement, insertion, and feedback. Before answering the questions, participants were given a brief overview and explanation of the study. The *elemental arrangement* task was performed first. The online survey in the feedback section asked the participants which arrangement of the symbol they agreed with and their thoughts on the importance of visual accessibility for the 4D Printing symbol design. Participants were asked if they agreed with the statement given that it was significant for communication in designing 4D Printing.

5.3.3 Data Analysis – Online Survey II

The data for the second online survey of the study were collected in December 2021, which was used to validate the symbol design as the communication tool for the 4D Printing design process. In this study, the researcher used a bar chart as in previous studies (see Section 5.2.3) to analyse the data. In analysing the data from this study, participants' answers were divided into two groups: designers and engineers. The reason to do this is to make sure the researcher gets valid data from both users.

Phase 1: Elemental Arrangement

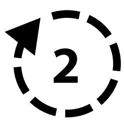


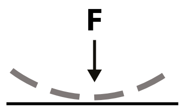
Arrangement 1 (**A1**) Arrangement 2 (**A2**) Arrangement 3 (**A3**) Arrangement 4 (**A4**)

Figure 65. Four Elemental Arrangements of 4D Printing symbols.

Phase 1 - Elemental Arrangement is the first task in this study. This task aimed to determine which arrangement of the 4D Printing symbol is suitable to represent the complete emerged 4D Printing symbol. Participants were asked to select only one of their most preferred arrangements symbol provided in this online survey. The set of four 4D printing arrangement symbols was served, as shown in Figure 65. Participants were not timed and were given sufficient time to determine their 4D Printing symbol arrangement preferences. The four arrangements represent the five elements for 4D Printing: shape changes, stimuli, timed sequence, speed, intensity and duration of stimuli being applied.

Table 17. Symbols description of the 4D Printing elements

Symbol		4D Printing Elements	Description of the type of the elements
1.		**Stimuli**	Stimuli-responsive polymers or smart polymers are macromolecules that are sensitive to specific triggers from the external environment. These materials change their characteristics if exposed to water, light, heat or magnetic fields, and chemicals.
2.	75°C 15s	**The intensity of the stimuli**	The quality or state of being intense especially: The amount of force/energy for the heat, light, sound, electric current, etc. per unit area, volume, charge, etc.
		Duration of stimuli	The length of time that of the trial or something lasts.
3.		**Timed sequence**	Set of numbers next to each other as a set order, a series or arranged in order.

4.	**11s**	**Speed**	Speed means the rate at which something or an object moves or the act or state of moving quickly.
5.		**Shape-changes behaviour**	Deformation of an object to another form in response to stimuli.

In phase 1 – elemental arrangement, participants were asked to select the preferred emerged symbol arrangement from four variant styles shown in Figure 65. Each of the symbols included: the elemental arrangement of the symbol representing the stimuli, intensity of the stimuli, duration of stimuli being applied, the timed sequence, speed of the shape-changing behaviour, and finally, the shape-changing behaviour associated with the 4D Printed part. Participants can refer to the meaning of each image in Table 17. Symbols description of the 4D Printing elements. The description for all five elements of 4D Printing symbols is also provided in the survey.

5.3.3.1 Result for Phase 1 - Elemental Arrangement

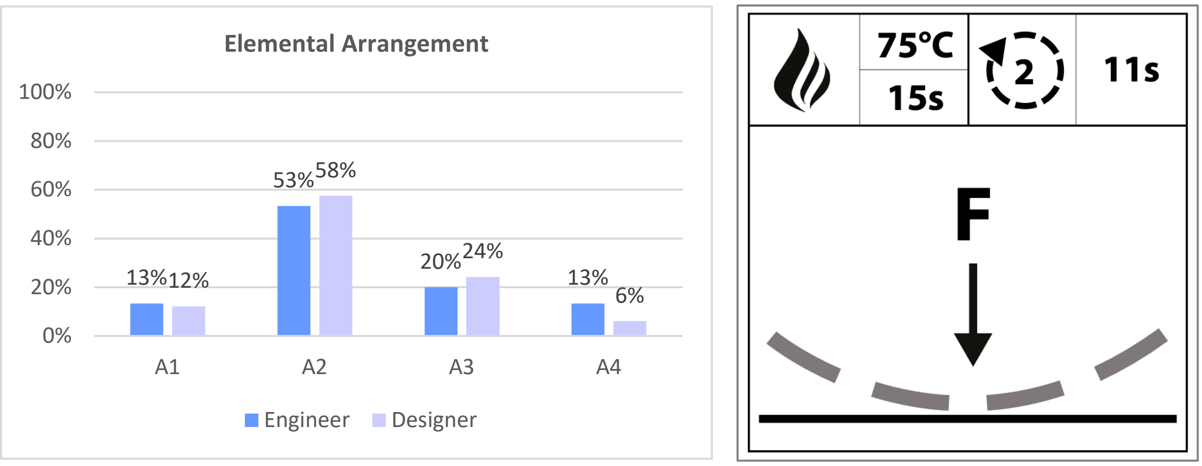


Figure 66. The chosen Elemental Arrangement of symbols.

The highest rates of preference to evaluate the final development of the symbol from this task. This result indicates that designers and engineers have similarities in choosing a preferred arrangement. *Arrangement 2 (A2)* was selected by a majority of the participants, with 53% engineers and 58% designers. Figure 66.The chosen Elemental Arrangement of symbols. shows the selected symbol design arrangement with five 4D Printing elements that emerged or united as one symbol to communicate 4D Printing in the design process. The results from the elemental arrangement task revealed that *Arrangement 2 (A2)* became the participant's highest rating to the preferable symbol arrangement, as shown in Figure 66. There was strong correspondence among designers. This result may be because the shape-changes behaviour symbol in *Arrangement 2 (A2)* is more significant and appearance than the other arrangement, as shown on the right side of Figure 66. With these arrangement tasks, this study can use the preferred arrangement for the 4D Printing symbol as a tool for designers and engineers to communicate with each other.

Phase 2: Insertion

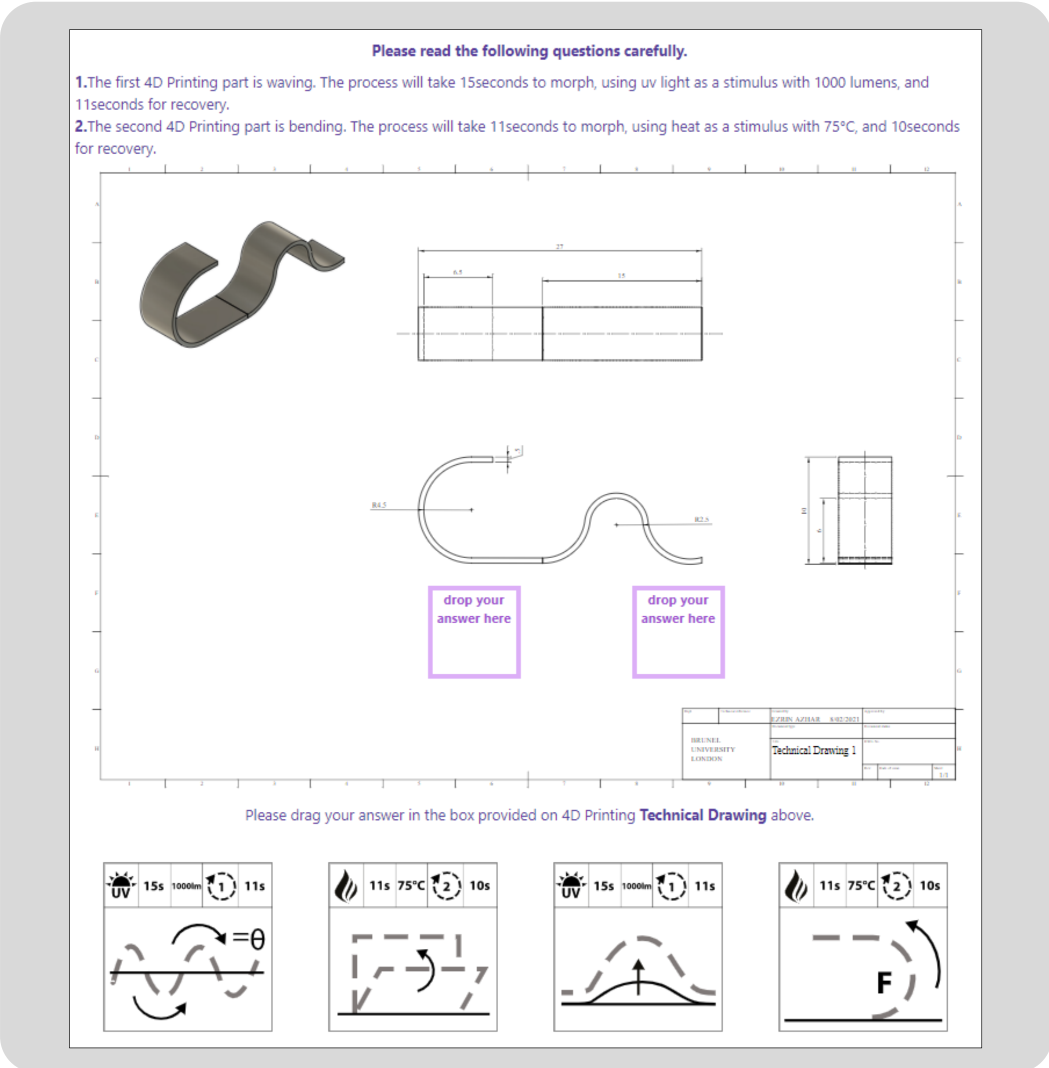


Figure 67. An example of a task in Phase 2 – Insertion

The survey provided all three tasks with two blank boxes to be filled by the participants. A short video regarding how the deformation of each task was included in each question: the video displayed in this task is to ensure the participants understand how the 4D Printing deformed their part related to each question given. In addition, participants can replay the video to ensure they are clear before answering the question. The example of the question in Phase 2 - insertion was presented to the participants shown in

The researcher also addressed the implementation of this communication tool can be used as a symbol in technical drawing since no existing 4D Printing symbols have been created. By emerging the elements of 4D Printing as one complete symbol, this task aims to examine the recognition and usability of the symbol. In the online survey phase two – insertion, three tasks were conducted in this study. Participants were asked to take drag-and-drop for transferring the proposed symbol in the correct boxes provided to answer the question given.

5.3.3.2 Result for Phase 2 – Question 1

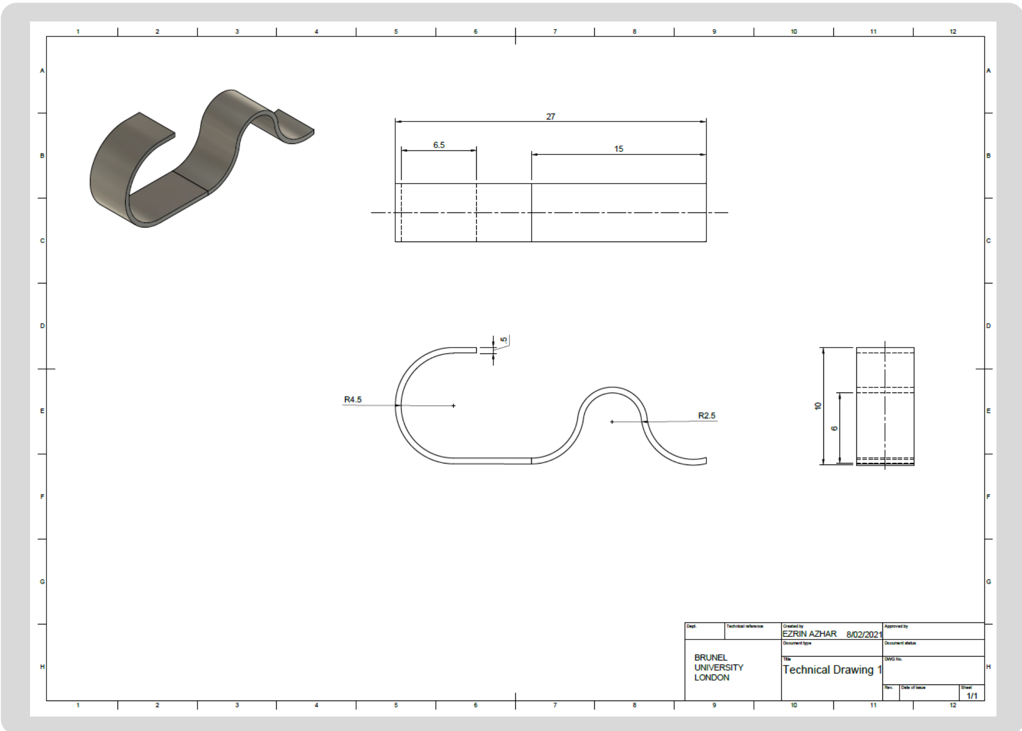


Figure 68. Question 1 – Phase 2

Figure 69a. shows the results from the first question in Phase 2 for the Bending and Waving symbol, in which participants must choose the correct symbols to drag on the technical drawing provided in Question 1, as shown in Figure 68.

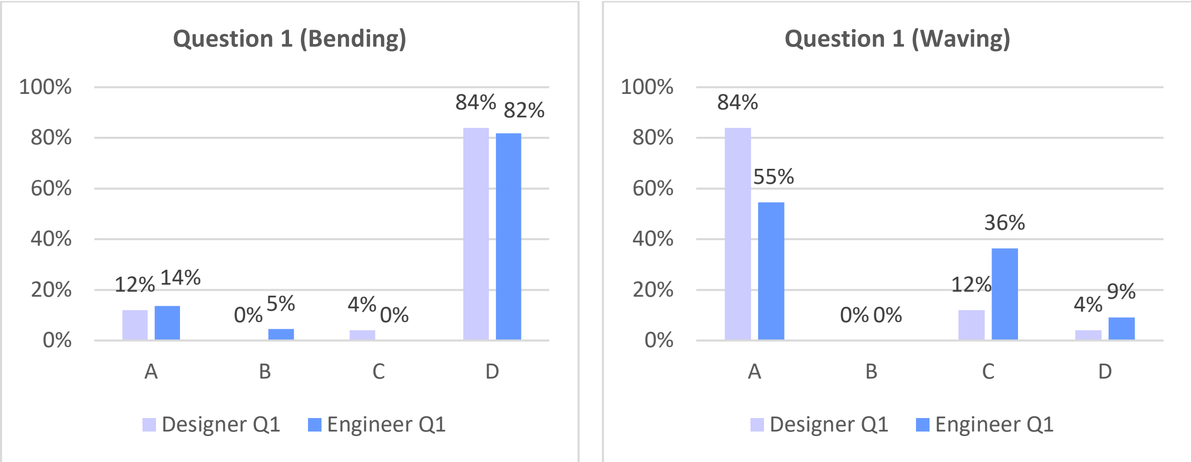


Figure 69. Results from (Insertion task- Question1—Bending and Waving)

The majority of the participants, from designers and engineers, answered correctly in this question, with Designer 84% and Engineer 82%. For the Waving symbol, the majority of designers answered correctly with 84%, while engineers with 55%. However, for the waving, some participants choose C with 36% engineers and 12% the designer. Where it represents 'buckling', the researcher assumed that this decision was made by participants who misunderstood the sample shape of waving with the buckling image, which led them to select the wrong symbol.

5.3.3.3 Result for Phase 2 – Question 2

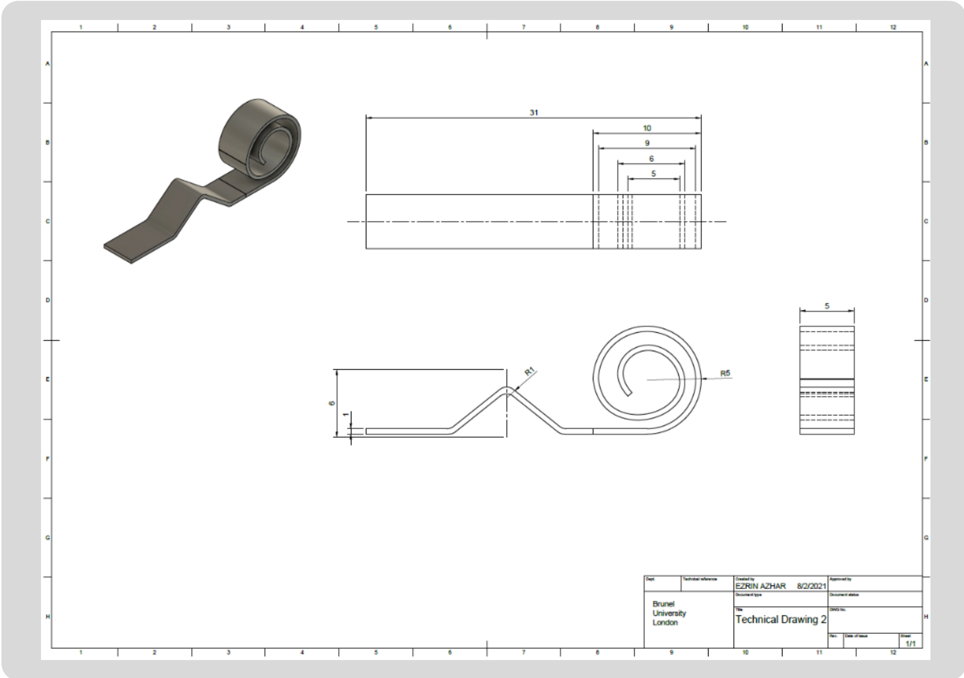


Figure 70. Question 2 – Phase 2

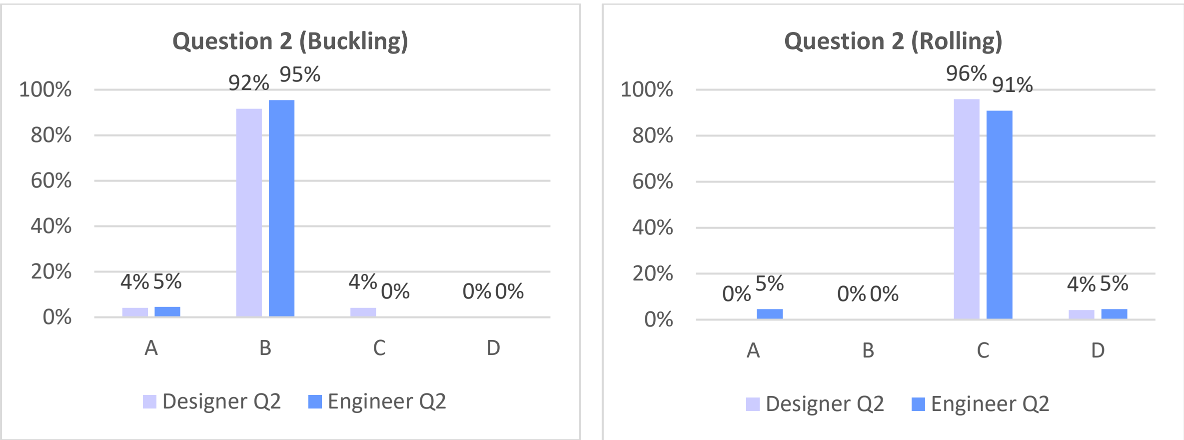


Figure 71. Results from (Insertion task- Question2—Buckling and Rolling)

Figure 70., presents the results from the second question in the 'insertion task'. Participants were asked to answer the correct symbols for the Buckling and Rolling symbol. There were tiny differences in participants' answers, as shows in Figure 71. It means that the designer and engineer agreed and understood which symbol represented the 4D Printing shape-changes symbol for buckling and rolling. The percentage of participants who correctly answered for *Buckling* is high, with 92% of designers and engineers with 95%. Similar results to the *Rolling*

symbol, the majority of the participants answered the question correctly, with 96% of designers and 91% of engineers.

5.3.3.4 Result for Phase 2 – Question 3

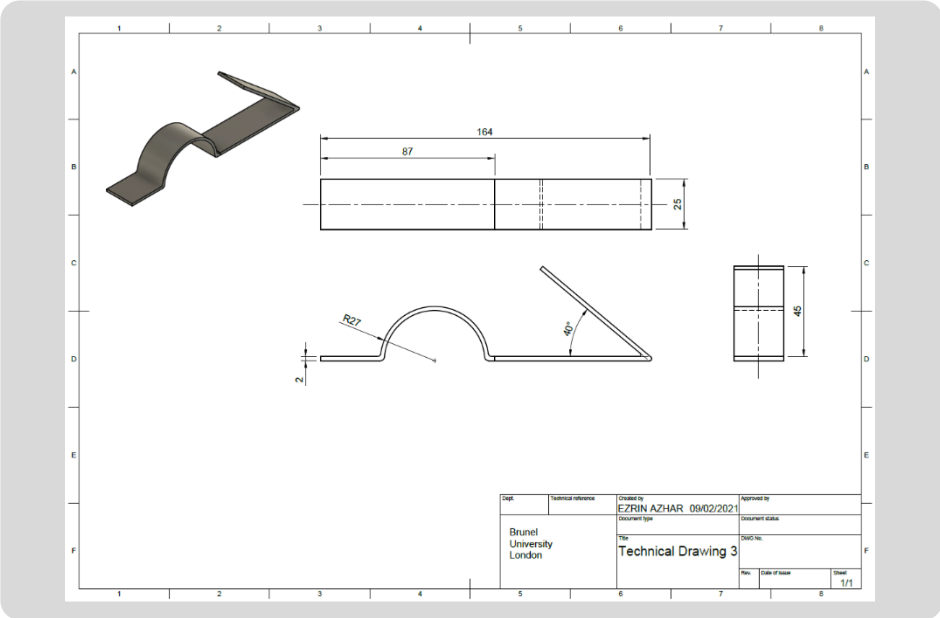


Figure 72. Question 3 – Phase 2
The third task question in phase 2- insertion illustrates in

Figure 72. The participant was asked to select the correct Topographical change and Folding symbol. The results are delightful; almost all participants answered correctly, as shown in Figure 73.

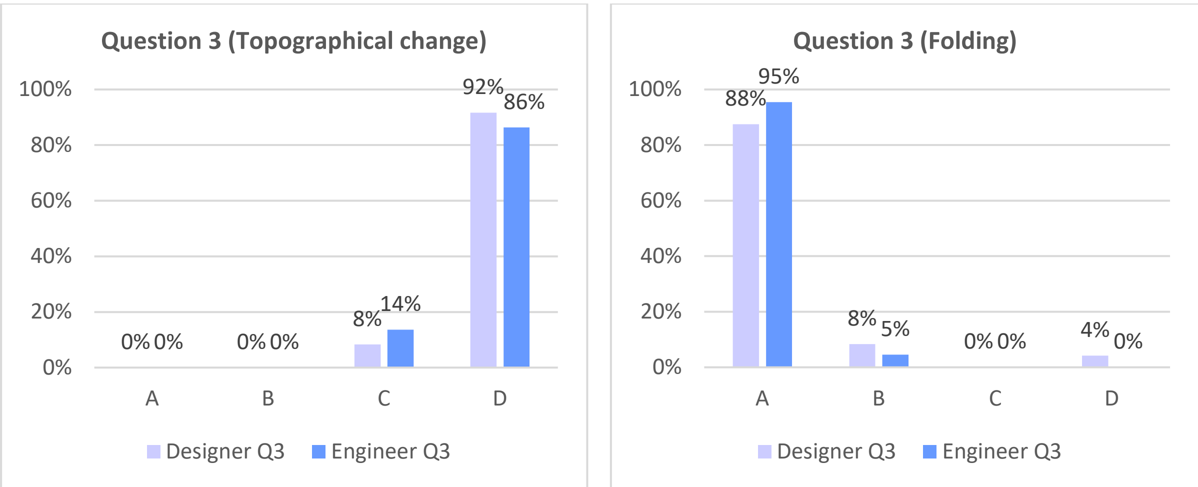


Figure 73. Results from (Insertion task- Question3—Topographical change and Folding)

Designer with 92% correctly answered and engineer with 86% for *Topographical change* symbol. For Folding, 88% of designers and 95% of engineers correctly selected the correct symbol to represent the folding symbol. The survey found that most participants chose the correct answer for all three questions in this Phase - Insertion task to evaluate the recognition of the 4D Printing symbols for communication tool from this study. According to participants' feedback, they informed that the animation provided was intended to help them better understand to match the 4D Printing symbol correctly and that they would later understand the meanings of the symbols. Next, after completing all three questions, participants continued to the final section to complete the feedback or questionnaire session.

Phase 3: Feedback

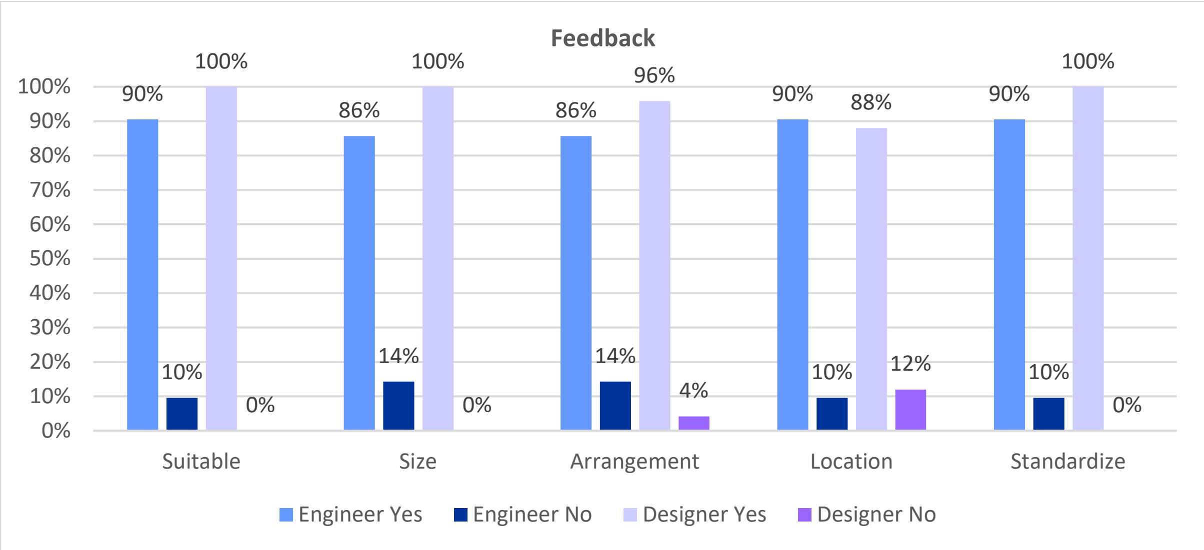


Figure 74. Participant's feedback results.

In phase 3 – feedback, participants were asked to fulfil a feedback form to follow up in detail. This phase serves the purpose of getting an individual perception of the participants. The researcher thought this might be needed in case some of them have some suggestions or problems regarding the survey questions. The survey contained multiple choice, *Yes* or *No* answer questions and no longer qualitative questions, although these were limited to maintain a reasonable response rate and prevent fatigue effects. The questions were developed based on the characteristic of the proposed design symbol for communicating 4D Printing. Participants from designers and engineers found the symbols very helpful in communicating the 4D Printing design process; their feedback is shown in Figure 74.

Participants were asked six questions related to visual accessibility to get their feedback regarding the 4D Printing symbol. As a measure of comprehending 4D Printing, participants were asked to decide if they agreed or disagreed with the questions about the symbol. If they did agree, the participant should click the *Yes* button. If they disagreed with the symbol's questions, they should press the *No* button. Positive feedback was received concerning the symbol's design usefulness and usability. The experiments show that designers and engineers can easily communicate using the approach symbols to the 4D Printing design part.

As shown in Figure 74, the first feedback question mapped out 4D Printing symbol usage with the following questions: *Are the symbols shown suitable to communicate the information for 4D Printed parts?* While the majority of participants agreed that the symbols are suitable to communicate in designing 4D Printing parts, 90% of engineering and 100% of designer backgrounds agreed with the statement. Next, for the second question, participants were asked about the dimension of the 4D Printing symbol. *Are the size of the symbols clear?* 86% of engineers agreed, same as the first question; all designers also agreed with the dimension for the symbol design. In the third question, when asked whether they were cleared, the participants were asked to answer *Is the arrangement of the symbols communicated clearly?* 86% of engineers and 96% of designers agreed that the symbol arrangement was clear for them to understand. The following question asked participants to give their opinion. *Do you think the location of the symbols inside the technical drawing is suitably placed?* As participants were asked to answer the Insertion task, which related to how the symbol can be applied (Section 5.4 – Phase2 Insertion), engineers with 90% and 88% of designers agreed on the place located for the symbol. In the final question, participants were asked, *Do you think having standardised symbols can help designers and engineers to communicate 4D Printing information?* 90% of engineers and 100% of designers agreed that the proposed standardised symbol could help improve the communication barriers in designing 4D Printing parts. At the end of the feedback question section, participants were encouraged to give a comment or their suggestions to improve the 4D Printing symbol. The comments expressed by the participants suggest that toolkit for the following reasons: Generally, positive responses were received regarding the usability and usefulness of the toolkit. Despite the variability in the results, the majority of the participants said that it was useful. While discussing the feedback, some participants suggested adding more elements, such as colours, type of material, pattern, thicknesses, size, etc., to the approached 4D Printing design symbols. Next, participants also indicated that they generally preferred and understood the symbol design well.

5.3.4 Discussion

The purpose of this study was to evaluate the design consideration which the 4D Printing design symbols as a communication tool for the user (designer and engineer). The researcher also learned which symbol design potential users preferred instead of making assumptions. There is a limitation of this study which some participants don't exactly know how to explain why they answered, and this is because they picked a design or were not interested enough in sharing their thoughts. This online survey presents findings from this study (Chapters 4 and 5) that were used to co-develop the conceptual framework for the communication tool symbol library for designers and engineers to communicate the design process of 4D Printed parts effectively. Results found that the use of symbols has the potential to represent better 4D Printing shape-changing behaviours and other elements of the 4D Printing process, thereby enabling better communication during the design stages [263]. The design and use of effective symbols as part of a communication system require excellent and thorough evaluation. In addition, there is still a lack of research on the 4D Printing communication tool in the current design process. Further challenges remain, including accepting these standardised symbols framework that needs to be recognised intentionally and within discipline-specific domains.

5.3.5 Validation of the 4D Printing Communication Tool

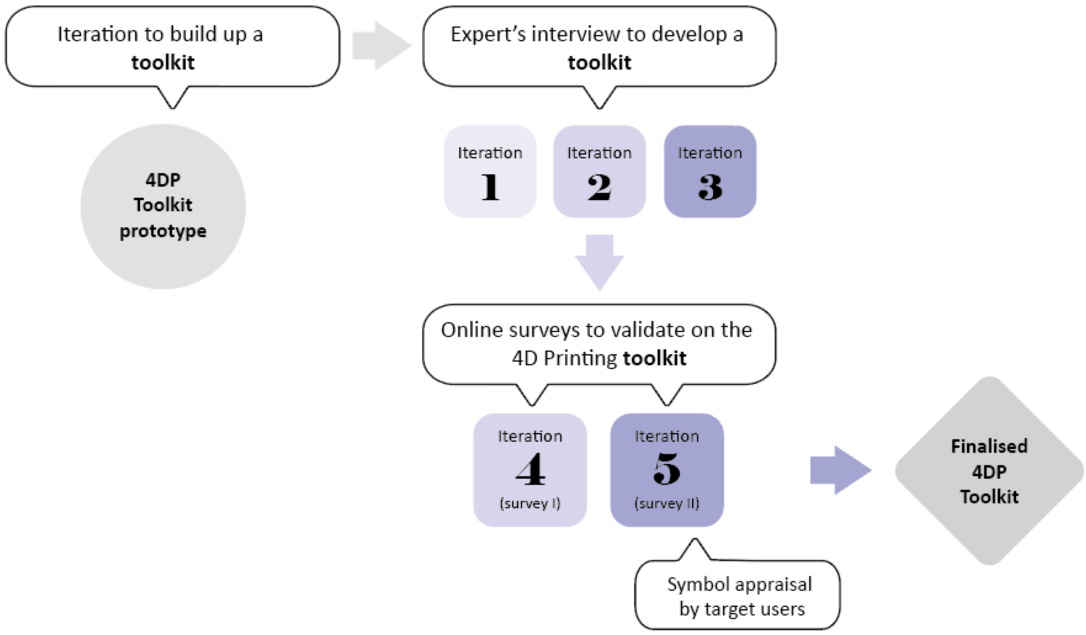


Figure 75. The developing process of the toolkit.

5.3.5.1 Development of the 4D Printing Communication Tool

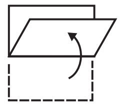
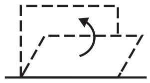
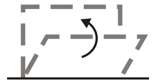
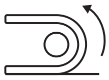
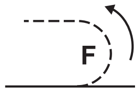
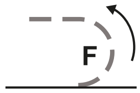
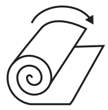
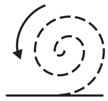
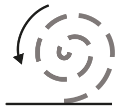
Whether spoken or written, human communication involves using words structured and conventional. The definition of semiotic in 'Peirce's Sign Theory' is the study of signs and the use or interpretation, where the signs can be classified into three types: symbol, icon and index (see Section 2.6.1.2). A symbol pattern refers to its object through interpretive habit or reference. The relationship is arbitrary or conventional rather than literal. However, a basic symbol is generally ineffective in communicating objective ideas. Instead, it can be refined and simplified to highlight and exaggerate its various characteristics. This type of symbol also has a variety of categories that can be used to identify the information. In this study, 4D Printing symbols convey communication for developing materials through processing, structural modifications, engineering design, and manufacturing. It is challenging to select which elements need to be added to the overall symbols. The symbol with good interaction will eventually assist the completion of in-depth communication between designer and engineer in designing the 4D Printing product.

Table 18. Process of the research instruments and tasks for the 4D Printing toolkit development.

Research Instrument	Description of the Research Methods
Iteration One	To understand the needs and challenges in communicating 4D Printing between designers and engineers, the researcher interviewed six experts to get insights into how 4D Printing is currently communicated in the field and their knowledge and preferences regarding the 4D Printing technology.
Iteration Two (Role-played)	Focus group 1 used observation of participants' sketches and discussions of those sketches and their attributes and meanings to their sketches. This study analysed how schematic concerns were intertwined in the marks/signs used to represent and communicate their ideas.
Iteration Three (Observational)	To define the type of symbols based on specific characteristics which make them usable, and these are considered before designing any symbols. This stage is further defined by the 11 types of 4D Printing shape changes behaviours. In this task, participants were asked to sketch the two sets of 11 shape-changes; the study found similarities between designers and engineers making marks to represent the characteristic of the symbols.
Iteration Four (Survey I)	This survey used the semantic differential to measure participants' evaluations of the symbols' aesthetic aspects. Participants were asked to click the most preferred symbol. The time to choose was limited, so only the most eye-catching symbol was selected.
Iteration Five (Survey II)	An online experiment was conducted to explore the degree of understandability and recognition of the tool to the user. The symbols used were those obtained from the online survey I.
(Evaluation)	Experts interviews involved participants from the British Standards Institution (BSI) and Technical Product Realization (TPR) TPR/1/3, Digital product definition (3D), and TPR/1/8, BS 8888 Technical product specification.

Validation of the toolkit is an important step of the design research process (see section 3.5.5). To evaluate whether the toolkit is appropriately made to use as intended. A popular evaluation of toolkits is in the form of iteration methods, as shown in Table 18, which have been adopted in many design studies for idea generation and for testing an inspirational tool practically [264]. The online survey's target in this research is to evaluate whether the toolkit can assist designers and engineers in increasing and eliminating the communication barriers of the design process for 4D Printing products. Designers and engineers also evaluated the information provided by the survey symbols to fit their needs better. Some examples of the developing process of the toolkit are illustrated in Table 19.

Table 19. The developing process of the 4D Printing toolkit for shape-changes behaviour.

Initial	First Development	Second Development	Final
			
			
			

Based on previous research results, some development from the initial symbol sketch until the final process in this research symbol library is shown in Table 19. The final symbol design was selected as the communication tool for designing 4D Printing. An iterative process was conducted to evaluate and explore participants' degree of the reliability, usability, understandability and recognition of the framework for the 4D Printing communication toolkit. Online surveys suggest increasing information retrieval tasks using the proposed 4D Printing symbol. Online data collection is provided more useable data than other data collection methods. Furthermore, participants' interactions with the online survey are standardised; as a result, interviewer bias is eliminated.

5.3.5.2 Symbol as a communication tool

The symbol has a good track record as a communication tool to transmit information. Based on the International Organization for Standardization (ISO), ISO 19,027 symbols, as visual expressions internationally, solve the communication barriers if the symbols are understandable and applied regardless of regional or cultural differences [265]. Hence, the designer uses visual representation as a tool for an external process in various ideas through visualisation. This plan effectively utilises skills and is also suited for designers to develop visual communication skills supporting their nonverbal arguments in 4D Printing. Several limitations are relevant to this study. This research only investigates the barriers to communicating 4D Printing in the design process. This research proposed symbols as a communication tool. The iterations validate the communication tool from (Chapter 4 and Chapter 5) in the form of online surveys. Then the final design is accomplished based on the feedback from the surveys. To the best of the researcher's knowledge, the study highlighted that no study had investigated standardised communication tools in designing 4D Printing products.

5.4 Chapter Summary

The study presented qualitative and explorative surveys in *Online Survey I and Online Survey II*. An online survey used generative and evaluative methods (see Section 3.6.4). To the study knowledge, this is the first study to create and analyse the toolkit for communicating the 4D Printing design process. The results of this online survey revealed that the designers and engineers could recognise, understand, and communicate effectively by having the standardised communication tool for visual accessibility. They also suggested that there should be a need for more inclusive design tools to help them improve their communication. Although the study results are valid, it is also possible to go beyond this feedback and develop a more comprehensive approach to rendering variability. From this statement, the study developed a more thorough *conceptual framework for a toolkit* for future work by applying the guideline of developing the communication tool to the actual design process and observing the communication when designing 4D Printed parts, which is explained in-depth in Chapter 6.

Chapter 6:

PROPOSING THE CONCEPT OF 4D PRINTING COMMUNICATION TOOL GUIDELINE

(DESCRIPTIVE STUDY II)

PROPOSING THE CONCEPT OF 4D PRINTING COMMUNICATION TOOL GUIDELINE

Chapter content

Chapter Six describes the development and iterative testing and revisions of the 4D Printing symbols framework applied to the 4D Printing symbols design toolkit, which was developed as a guideline to communicate the shape-changing behaviours of the 4D Printing process. The chapter outlines the toolkit's developing activities to gain feedback about its completeness, effectiveness, and usability from engineers, designers, experts, and students. The chapter is summarised with the final version of the 4D Printing design toolkit. The toolkit has been published in a peer-reviewed journal [266].

6.1 Introduction

In this Chapter 6, the study considers a conceptual framework for the 4D Printing toolkit, which tailors the elements according to the specific needs of designers and engineers to communicate in designing the 4D Printing process. The chapter complements and questions the existing barriers around the conceptual perspective that inform the research process. The primary aim is to provide designers and engineers with a tool for standardised communication while designing 4D Printing products.

A conceptual framework is a collection of concept ideas created using qualitative processes that represent the process of theorization with diagrams. The study explored the process of developing a conceptual framework for the 4D Printing design process by defining the concepts and procedures. A conceptual framework is an analytical tool that can have several variations and contexts. It may be applied in different categories of work where an overall picture is needed and is used to make a conceptual distinction and organize ideas.

A framework is a tool used to structure the approach to a problem. In many ways, it acts as a lens to help focus the researcher's attention on specific aspects of the problem and gives focus to the analysis within the research study [267]. Moreover, it can tell the researcher what to look at, and as it is often based on theory, it also tells the researcher why they need to look at those aspects. There are many different types of frameworks. Some are used to understand the current situation with measures or indicators. Others are used as a guide to making comparisons across time or space, while some provide a common language for researchers. Certain ones are used to help diagnose the problem, and some are used to assess the effectiveness of the action.

Furthermore, these categories are not exclusive and more than one might apply to the same framework. As the framework is used to help frame the problem for researchers, the chosen framework must match the research questions. If it matches, it should build on the data and add to the understanding of the results. However, if it does not match, it will not substantially influence the researcher's results.

In this section, the study proposes a new communications framework to aid specific communication of aspects necessary to design 4D Printing objects. This communication framework includes communication elements of shape changing behaviour, stimuli response, timed sequence and recovery time. Then, the prototype 4D Printing communication toolkit is implemented that can generate standardised graphical symbols that can be used by designers and engineers in 4D Printing projects.

6.2 Proposing the Concept of 4D Printing Communication Tool

> *"A conceptual framework explains, either graphically or in narrative form, the main things to be studied – the key factors, constructs or variables – and the presumed relationships among them." - (Miles and Huberman, 1994, p.18) [267]*

The conceptual framework proposed in this study aims to provide a guideline or a systematic methodology that facilitates the design process for the 4D Printing communication tool. There is no doubt that 4D Printing is not a simple printing process and requires a combination of several components. To address these issues, this study developed a conceptual framework to enhance communication between designers and engineers when designing 4D Printed parts. The concept of the 4D Printing communication toolkit has variations and context, which illustrates what is expected to find through the research. It defines and visualises the relevant variable for the study, maps out how they are related, and organises ideas. The research on the conceptual framework answers (1) which variables are relevant to the study, (2) how to define variables during data analysis and (3) interpreting model results.

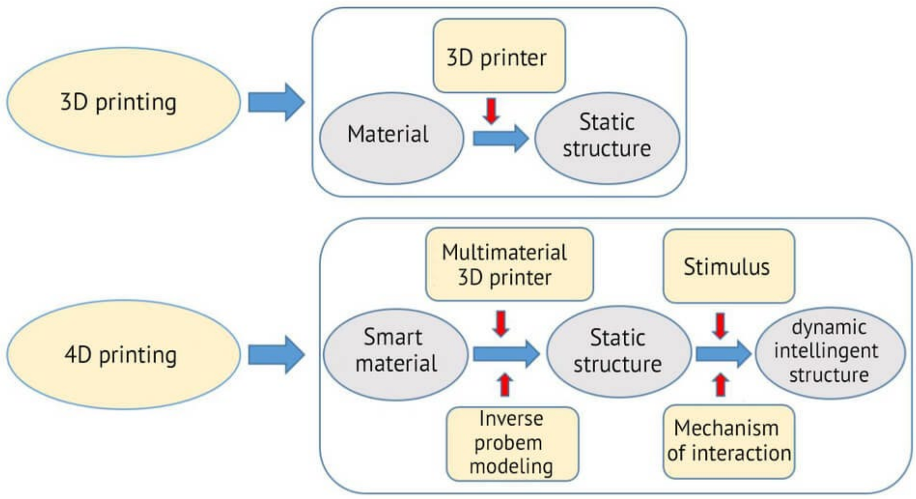


Figure 76. Adapted diagram from F. Momeni et al. / Materials and Design 122 (2017) 42–79], re-drawn by Jean-Claude André | Scientific Advisor at INSIS [268]

Figure 76. presents the 4D Printing process diagram in relation to the 3D Printing technology [55]. This study proposes a conceptual framework as a guideline for the 4D Printing symbols

library adapted from the 4D Printing process above. The intended users of this library are designers and engineers in the design 4D Printing process stages.

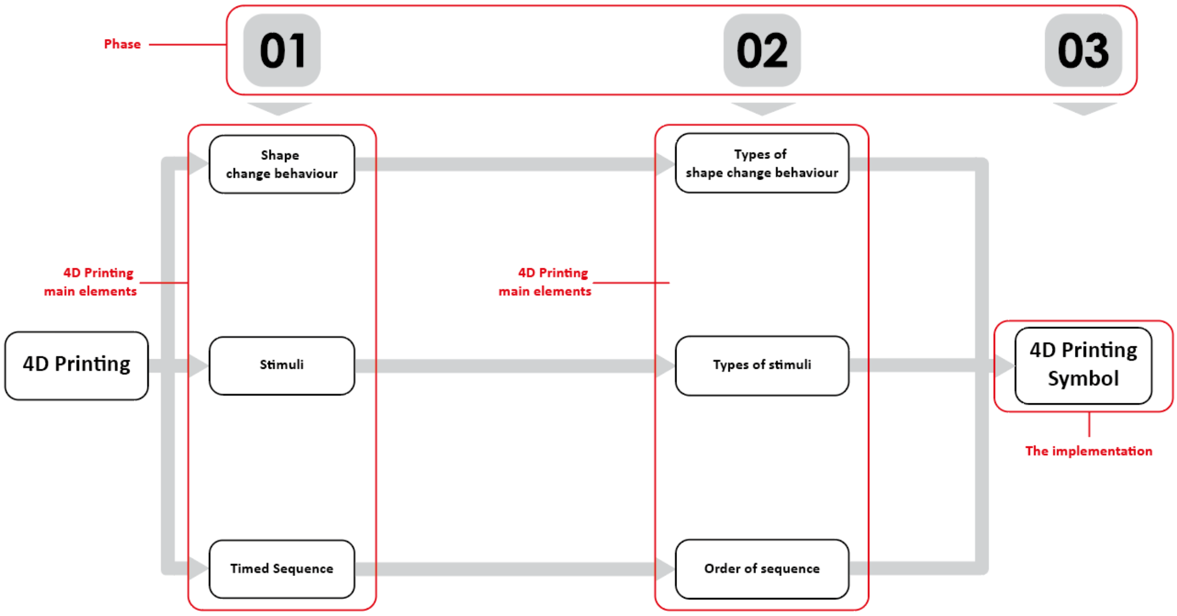


Figure 77. Stages of the 4D Printing communication tool guideline.

This study attempts to develop an effective 4D Printing symbol system. This research provides a conceptual framework to support the right approach and methods for designing a tool to communicate 4D Printing. The 4D Printing concept toolkit aims to improve the symbol implementation of 4D Printing communication. As a conceptual framework for communicating the 4D Printing design process, it is intended to support only the main aspects of 4D Printing elements in this research. There are three main components: the 11 shape-change behaviours, the 5 types of stimuli, and the order of timed sequence. This proposed conceptual framework for the 4D Printing communication tool should enhance the communication between designers and engineers in designing 4D Printing parts. To frame a crucial part of the conceptual framework design system, the general phase is placed in the boxes and listed specific variables under those phases. In this study, the conceptual framework is divided into three phases: ‘consideration’, ‘elements’, and ‘implementation’, as shown in Figure 77.

6.2.1 Stages in the 4D Printing Conceptual Framework Toolkit

The 4D Printing Conceptual Framework Toolkit is a three-stage conceptual framework that describes the communication processes that occur before, during and after designing, with a special emphasis on factors that might influence 4D Printing design. This study has proposed a conceptual design framework for 4D Printing symbols as the 4D Printing communication tool development guideline. This section presents the three stages required for the proposed guideline of conceptual framework based on 4D Printing elements.

Stage 1: Consideration

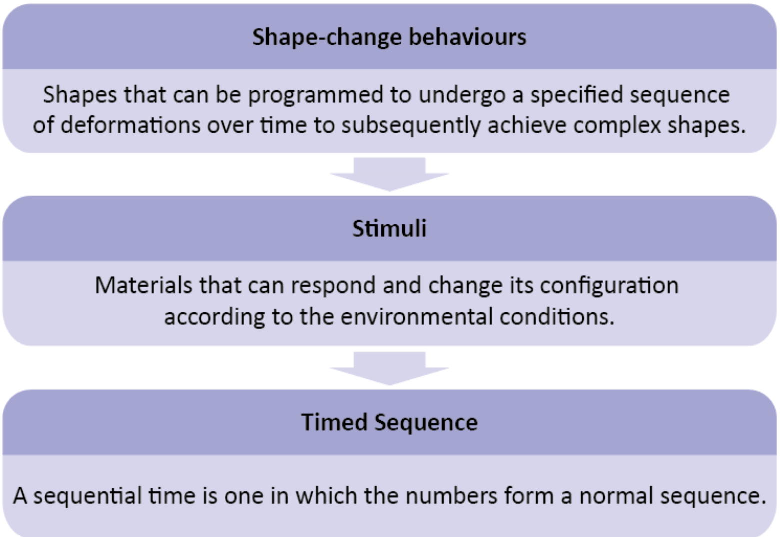


Figure 78. The consideration stage in the conceptual framework to communicate 4D Printing.

The first stage of the Conceptual Framework for the 4D Printing Toolkit requires specific considerations. According to Collin English Dictionary, consideration should be careful thought or attention, especially when planning or deciding to do something. The **consideration** stage is where the three main elements of 4D Printing are identified as shape-change behaviour, stimuli and timed-sequence (see Section 2.3). This stage allows designers and engineers to be kept in their minds in making decisions and evaluating facts before they decide to communicate the design process of 4D Printing. Furthermore, every stage and variable is connected in the first stage of the 4D Printing symbols conceptual framework. The first element of the framework is the *shape-changing behaviour*. It is an action of the 4D Printing objects that can be deformed, for example, folding, bending, twisting, etc. The second element is the external *stimuli* that enable the shape-changing ability of the 4D Printing objects. And the third element is *timed sequence,* indicating the order of object actions that should occur and the duration of those actions.

Stage 2: Decision

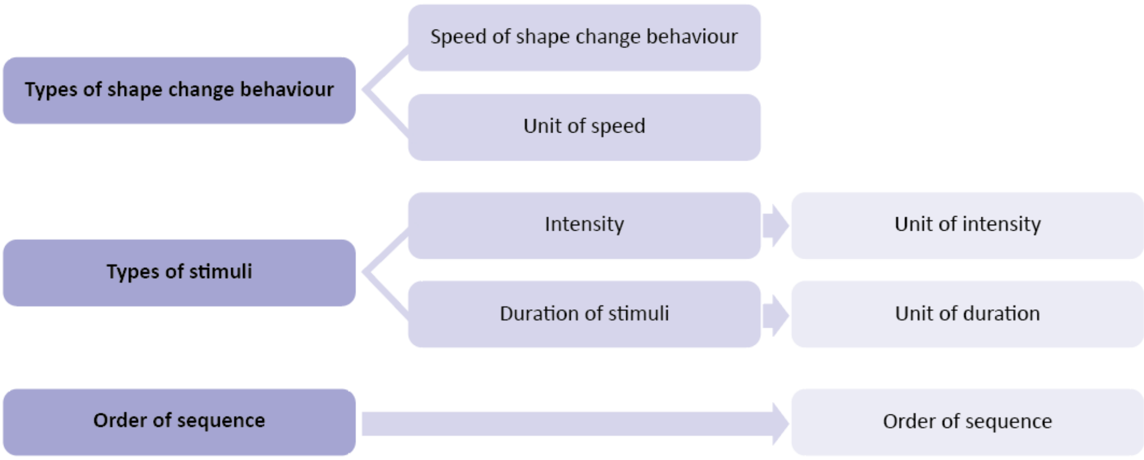


Figure 79. The decision stage in the conceptual framework to communicate 4D Printing.

The **decision** is the second stage, which defines the components required in order to support the communication elements. Users will need to select each component to influence their design process of 4D Printing. In this stage, the framework specifies all the details of 4D Printing main elements with the list of components. The first component is the (type of shape-change), listing the 11 shape-changes of 4D Printing: folding, bending, rolling, helixing, twisting, waving, curling, curving, topographical change, buckling and expansion or contraction. Then, it will bring to the (speed of shape-change), speed here taken from where 4D Printing can change shape over time. To show the accuracy deformation time of the shape-changes, this research added another variable called the (unit of speed). The International System of Units (SI) contains the unit of time with a symbol to define millisecond, second, minute and hour. Next, the framework divided it into two categories for the stimuli variable where all of it connected. First is the (type of stimuli), where it listed five common stimuli: heat, water, magnet, UV light, and pH level in the dotted line box. Moreover, 4D Printing is a known object made by 3D printed with time adding response and external stimuli, so need an (intensity). The (unit of intensity), Celsius, Fahrenheit, Tesla, Lumens, and hydrogen power are defined. Then, (duration of stimuli), which is related to (unit of duration), also using the

(SI) to show 4D Printed object takes time to morph or recover. Lastly, added (order of sequence) to describe the timed sequence to arrange the order for the 4D Printing deformation process.

Stage 3: Implementations

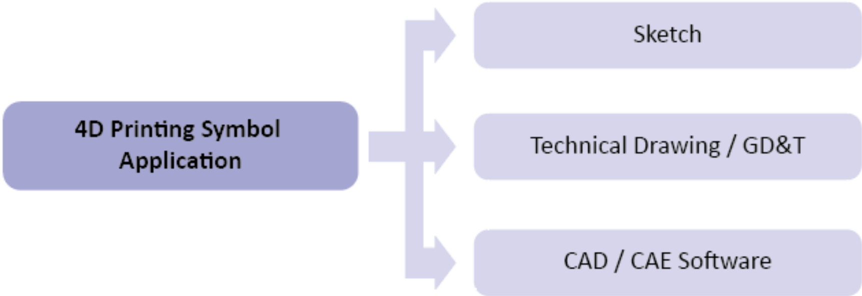


Figure 80. The implementation stage in the conceptual framework to communicate 4D Printing.

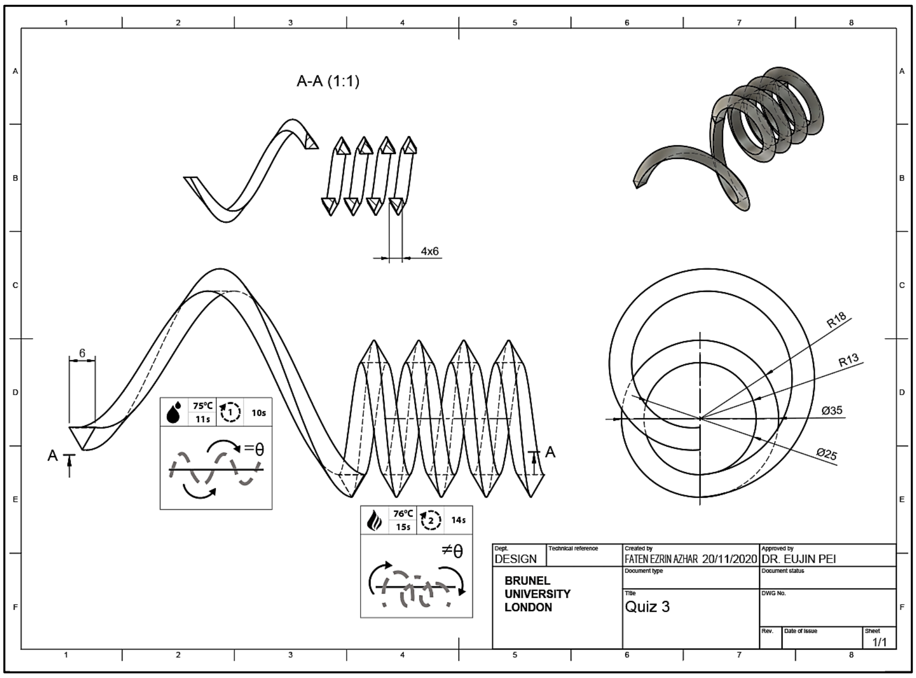


Figure 81. Illustration of an example of a 4D Printing toolkit used in technical drawing.

This third stage in Figure 80 focuses on the framework implementation of the communication tool. The concept of implementation refers to the practice or execution of a plan, method, design, specification, or standard for the design and manufacturing process. It refers to the actual implementation of how and where designers and engineers can use this 4D Printing communication tool to communicate. This communication tool can also be applied in the early design stage, where designers use sketches or hand drawings to visualise their idea. In addition, it can also be used in technical drawing, which engineers or product designers use before the manufacturing process, as Chapter 5 evaluates the communication tool using technical drawing. 4D Printing symbols can also apply in Computer-Aided Design (CAD) software. It can help increase productivity, improve the quality of designs, and effectively communicate design information for the manufacturing process. Currently, it includes only 11 shape-changing behaviours commonly used in 4D Printing. However, designers and engineers can combine symbols from other tools to fulfil these functions. Figure 81 illustrates how the final symbol can be used in technical drawing when designing 4D Printing objects. The symbol arrangement was finalized in Chapter 5, which combines all necessary elements to describe 4D Printed behaviour properties.

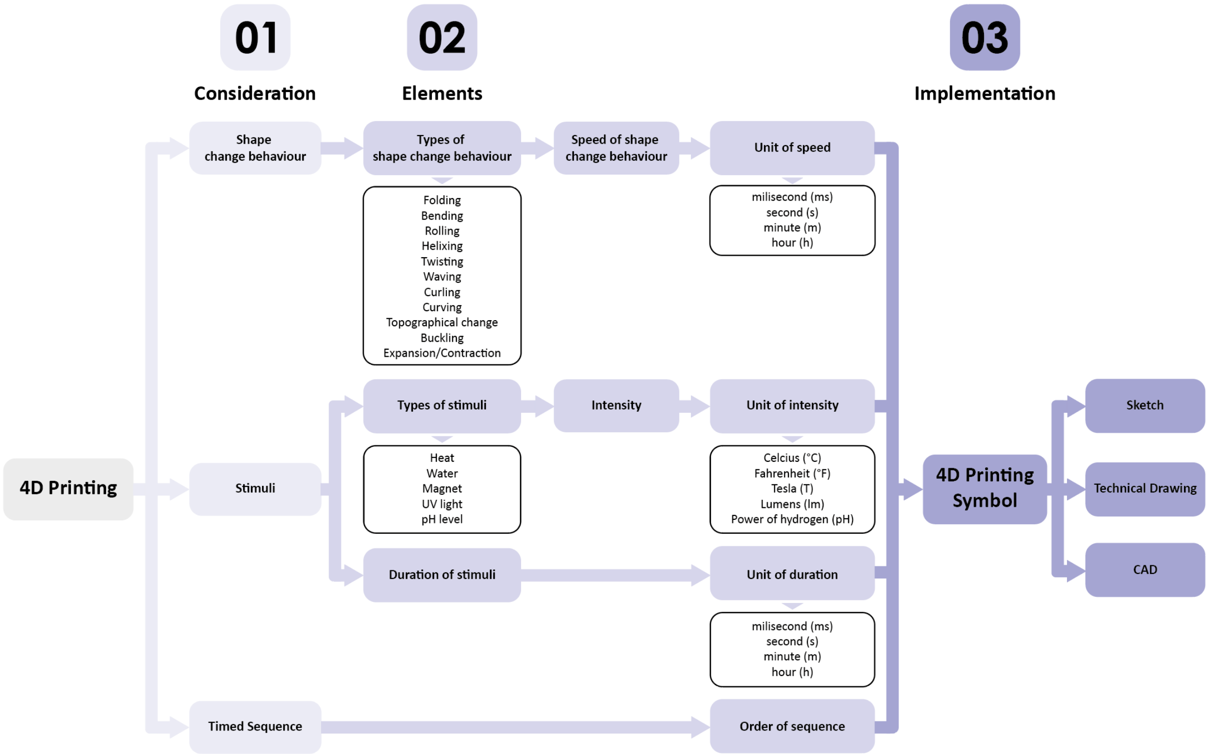


Figure 82. Final Conceptual Framework 4D Printing Communication Tool (Symbol).

Figure 82 shows the refined conceptual framework as a guideline supporting the toolkit that enabled designers and engineers to communicate the process of designing 4D Printing products. This proposed framework offered a clearer picture of creating the standardisation communication tool using symbols in 4D Printing. The study also provided further information regarding the 4D Printing elements supporting the communication guideline for other implementations since no existing 4D Printing communication tool has been created.

6.3 Practical Implementation of 4D Printing Concept Toolkit Prototype

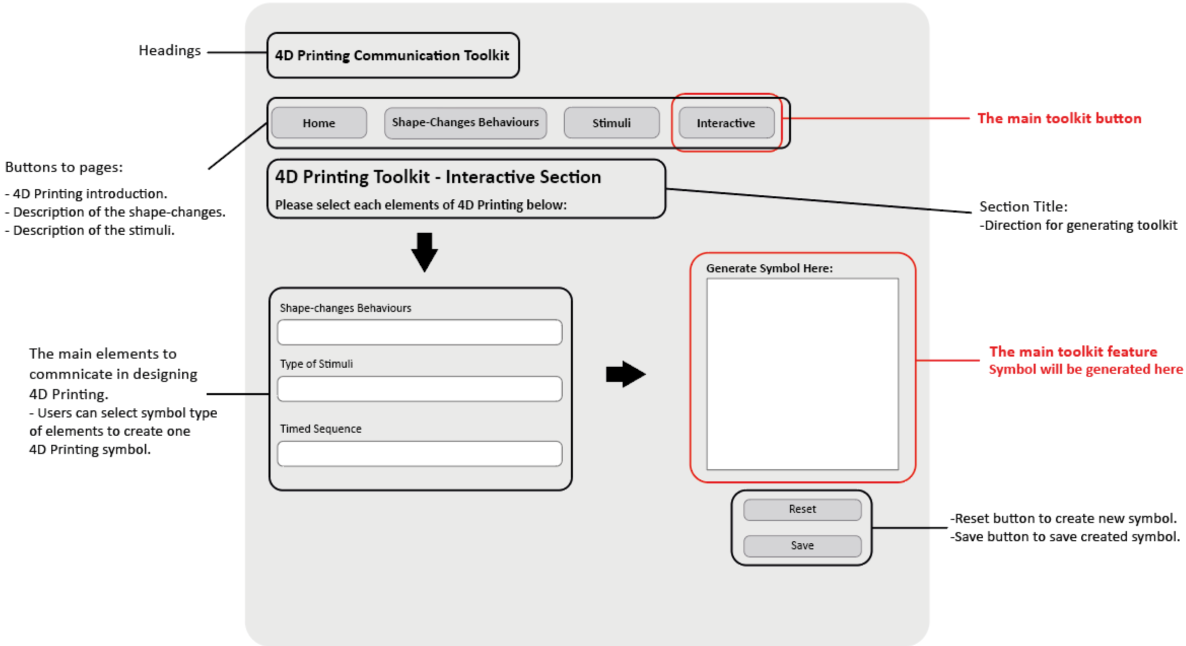


Figure 83. An example of the concept layout for a toolkit webpage

The practical implementation is concerned with the actual situation with user experience rather than involved with just ideas or theories. The idea's visual representation is called a prototype, where a prototype allows testing the ideas directly with users before developing them into a fully-fledged product. However, before spending time, money, and resources on creating and launching a new product into the market, the designer will use the prototyping model to answer three aspects: (1) does the product solve the user problem? (2) does the product score high on user desirability? (3) is the product user-friendly? Designers use the visual representation of their idea by testing it with the teams' members and testing it with the target user. The target users are those who will ultimately use the product, so getting feedback from the users is very important. The prototype can also be used as a communication tool between designers and engineers, especially for different teams, where it effectively communicates the idea.

6.3.1 Layout of 4D Printing Communication Toolkit Prototype

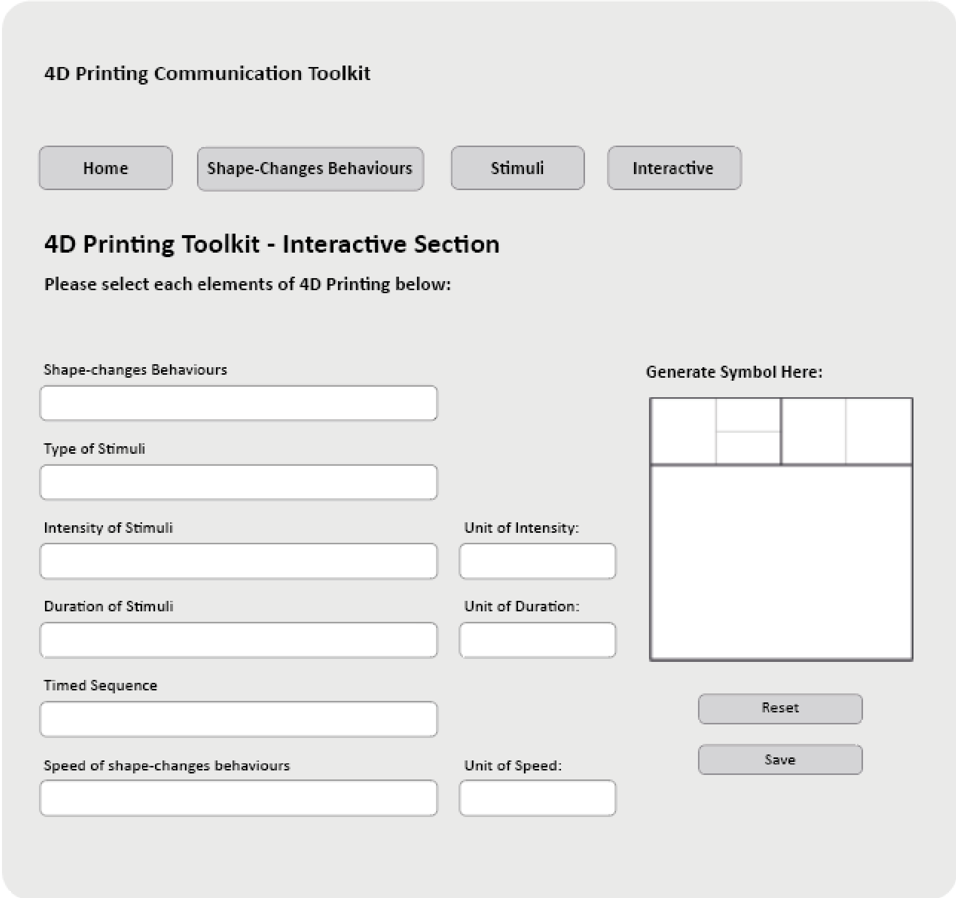


Figure 84. A framework of the second toolkit web page.

The layout is how parts or sections of the prototype are designed, arranged or laid out. A website layout is a set of elements that are arranged in a way that helps guide the user experience. Intentionally positioning the various visual elements can improve the user experience. In this section, this study explains the process of the arrangement of the proposed communication toolkit in designing 4D Printing. The layouts of current design toolkits in the form of websites were reviewed and analysed.

This toolkit replicated a typical user interface of the communication in the interacting design idea generation process. This section presents the prototype of the 4D Printing Toolkit for communication, which was modified regarding the feedback from the experts' interview (see Section 6.4). The illustration in Figure 84 shows information about the 4D Printing toolkit prototype along the top tab to guide users using the toolkit. After finalising the conceptual framework of the 4D Printing symbol, the researcher created a webpage link: ***https://symbols.ezrinazhar.com***, which has been shared for evaluation by representative users. The templates of websites of the 4D Printing communication toolkit were classified into four categories based on four pages or buttons, as shown in Figure 84. This concept of the 4D Printing communication toolkit layout is used as a guideline for how users can use it. When users have completed adding all the selected elements, they can generate the emerged symbol, which is unified of all elements (see Section 5.5.3) and save it to share among their team. The concept of the 4D Printing communication toolkit provided a simple step-by-step guide to support users, especially designers and engineers, in the design process.

6.3.1.1 The Menu Buttons

Figure 85. Illustration of the menu buttons for the toolkit.

This research provides a responsive user interface on both desktop and mobile. Every page on this website shows the title of the toolkit (4D Printing Communication Toolkit). On the top level, after the website's title, is called a navigation bar, the first thing users will see in this 4D Printing concept toolkit, as shown in Figure 85. These menu buttons or keys contain links to help users navigate the webpage prototypes to four different pages and features: I. *Home* button, II. *Shape-change behaviours* button, III. *Stimuli* button and IV. *Interactive* button. The ***Home*** button navigates the user to the website's first pages, which contain the introduction to 4D Printing and the concept of the 4D Printing communication toolkit. For the ***Shape Change Behaviours*** *button*, the user will be introduced to each of the meanings of the eleven shape-changes behaviours. Next, the ***Stimuli*** button will describe the five types of stimuli for 4D Printing. The fourth button is the ***Interactive*** button, the main focus of this proposed prototype toolkit, where the users can interact to generate 4D Printing symbols.

6.3.1.2 Application Features in Interactive Page

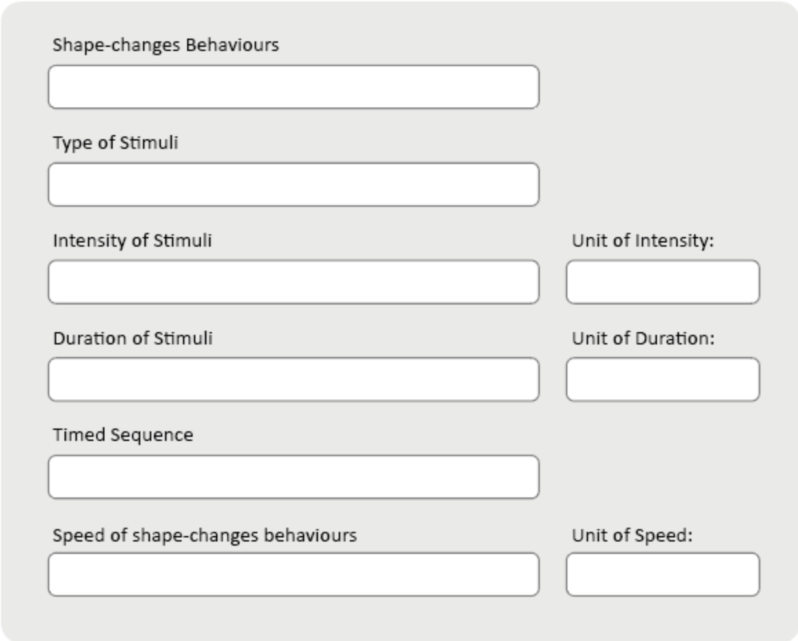


Figure 86. Illustration of the application menus for the toolkit.

Table 20. The drop-down application menus list.

Application Menus	Drop-down list
Shape-changes behaviours	The eleven shape-changes behaviours are folding, bending, rolling, helixing, curving, waving, twisting, curling, topographical changes, buckling and expansion and contraction.
Type of Stimuli	The five types of Stimuli are heat, water, magnetic field, pH Level and UV Lights.
The intensity of the Stimuli	The number of intensity to add by the user.
Unit of Intensity	The Intensity is measured in the unit of: **°C** for Celsius **°F** for Fahrenheit **T** for Tesla is the unit of magnetic flux density. **lm** for Lumen is the unit of luminous flux (a quantity of light source) **pH** for the level of potential of hydrogen to specify the acidity.
Duration of Stimuli	The number of duration to add by the user.
Unit of Duration	Milliseconds, Seconds, Minutes and Hours.
Timed Sequence	The shape-changing behaviour deformation order.
Speed of shape-changes behaviours	The number of times to add by the user.
Unit of Speed	Milliseconds, Seconds, Minutes and Hours.

The interactive page is the important part of this research study which is the main focus of the website prototype. On the interactive page, users will be presented with the application menus. Figure 86 above illustrates the layout of the application menus for the interactive page from the toolkit prototype. The application menus display vertically across the screen as the drop-down menu. Table 20 shows the drop-down list of actions the user can select based on their 4D Printing design parts, which are: *Shape-changes behaviours, Type of Stimuli, Intensity of the Stimuli, Unit of Intensity, Duration of Stimuli, Unit of Duration, Timed Sequence, Speed of shape-changes behaviours* and *Unit of Speed.*

6.3.1.3 The communication toolkit.

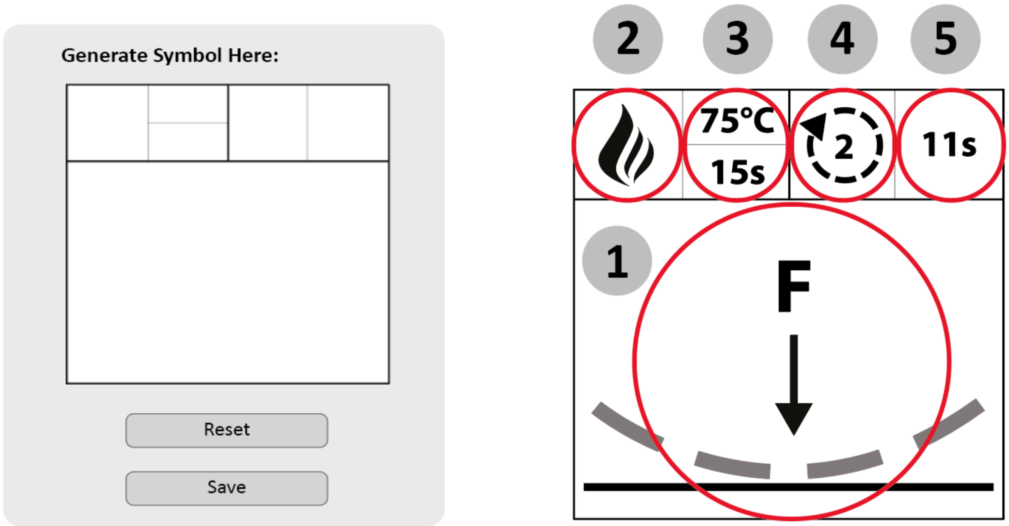


Figure 87. Illustration of the idea generation for the toolkit.

Figure 87 illustrates the image example of the 4D Printing communication tool for the interactive webpage prototype. On the left side presents the blank box contained with six divided boxes. Each of the six boxes then fills by the user with the 4D Printing elements (see Section 5.3.5) from the application menus. On the right side, it shows the example of a symbol filled with the 4D Printing elements. 1. The shape changing behaviour box on the bottom part. 2. Type of the stimuli on the top left side of the box. 3. The intensity and duration of the stimuli. 4. The order of timed sequence to fill by the participants. 5. The recovery time for the shape-changes behaviour. Next, under the arrangement box of the toolkit, there are two option buttons with the label *Reset* and *Save*. The *Reset* button uses to clear the created symbol or errors and brings the arrangement box to the initial condition. The *Save* button allows users to save the created symbol as an image straight from the website and share it with other designers or engineers in designing or experimenting with the 4D Printing products.

6.4 Validation of Concept Toolkit

A usability evaluation is a process that focuses on user experience or how well a product can be used to achieve its goals. It involves collecting feedback from users about the various aspects of the product. This process can be carried out through various methods to gather user information (see Chapter 5). A usability test is a method that involves evaluating the process of the product or service with a representative group of users. The objective of the evaluation is to identify the factors that can negatively affect the user experience and determine the product's satisfaction. The toolkit's design was initially developed to explore the various requirements of 4D Printing elements. The final layout of the communication prototype was then refined to include the necessary layout and contents.

After the prototype toolkit was created, this study conducted an expert interview to give feedback on developing the communication framework for the toolkit. In the published journal, this research discussed the results from the expert's interview to evaluate the design principles of a conceptual framework for the 4D Printing communication tool. The validity of the results has been evaluated through the iterations methods (see Chapter 4 and Chapter 5) and expert interviews. An unstructured interview is a type of interview that doesn't involve the preparation of a set of standardized questions. This type of interview differs from a structured one, which usually offers a set of questions. The researcher collected qualitative data through an unstructured interview by asking open-ended questions. This type of interview allows the participants to talk about their thoughts and feelings in a deeper manner. An evaluation interview usually involves the researcher reading or asking the questions to the participants and then recording the responses while interviewing the participants.

To refine the conceptual framework for the communication toolkit, expert evaluations were conducted through online Zoom interviews and face-to-face meetings on June 25th, 2021. Participants from the British Standards Institution (BSI) and Technical Product Realization (TPR) TPR/1/3, Digital Product Definition (3D), and TPR/1/8, BS 8888 Technical Product Specification, were involved in the interview process (see Appendix 7). Their feedback was used to shape and improve the content of the toolkit's conceptual framework. The feedback from the British Standards Institution (BSI) as industry experts is crucial for the design representation "symbol" and the concept of the communication framework toolkit to effectively communicate the 4D Printing design process. The BSI's knowledge and experience in technical product specification and digital product definition can greatly contribute to the development of a communication tool that can bridge the communication gap between designers and engineers. Their feedback can help ensure that the toolkit aligns with industry standards and best practices, making it more widely adopted and applicable in various design and engineering projects.

The expert interviewed were asked four questions regarding the 4D Printing communication symbol. The question answered by the experts are as below:

1. What are your thoughts about the proposed symbols for communicating 4D Printed Parts? / (CA4D?)
    a. **BSI:** It is a new interesting technology with no specific standardisation in communication. It is interesting in the way it communicates not only the geometrical dimensioning but also the behaviour of the 4D Printing, in terms of how those parts expend to react or how they will behave. (See Appendix)
    b. **TPR:** In terms of aesthetics, the symbol produced by the framework looks nice and clear. Timeless and fascinating.

2. How could these symbols be implemented? Into a technical drawing or within a CAD model as a 3D Annotation (Product Manufacturing Information or Model Based Definition?)
    a. **TPR:** It is relatable to some of the GD&T symbols of communication methods. It could be used in technical drawing or a CAD system after it gets standardised.

3. How can we further improve the symbols? (clarity, level of communication, graphic interface, compatibility with other symbols)
    a. **BSI:** Animated model might cover some of that stuff [4D Printing behaviour] as simulation animated symbol to represent the 4D Printing design.

4. Is there an opportunity for this as a Joint-standardization project?
    a. **BSI:** Yes. However, to standardize the symbol, a proposal of [4D Printing Design] needs to be sent to check with BSI 236261 to specify future work. This guide aims to help designers understand how data can be used to develop various standards. It can provide guidance on the types of data that should be included in the development process and the criteria that should be followed to inform the decisions that cover data interpretation and the decision-making process.

In this study, the experts were asked to provide their thoughts on how the proposed conceptual framework could be used as a guideline in supporting the user in communicating the design process for 4D Printing. The feedback from the participants was generally positive. The study analysed all the information, comments and suggestions collected through the questions session at the end of the presentation and distilled them into a summary. The Insights from the expert's interview session for the proposed conceptual toolkit for communicating 4D Printing design were highly valued, and they efficiently helped to communicate in designing the 4D Printing process.

Positive feedback was received from the interviewees regarding the visual recognition and usability of the proposed concept of the communication tool was well designed and suitable for communicating the 4D Printing design process. The experts mentioned that the framework was well-designed and that the role of user-centred design was also important in developing the 4D Printing communication tool. Experts also identified the toolkit as *timeless*. According to Merriam-Webster Dictionary, timeless means the subject is not restricted to a particular time or date. It also refers to something not affected by time, for example, the timeless appeal of the visual designs, which are always valid or applicable. The proposed concept of the communication tool design was highly valued, and it helped the user to communicate effectively to generate ideas in the design stage for 4D Printing.

6.4.1 Discussion

A framework is a conceptual structure intended to help guide the development of the 4D Printing design process. It can also support building other structures designed to expand the project's scope. Designers and engineers communicate information through instructions, identifying controls and signage. The purpose of a symbol dictates the specific visual attributes and requirements necessary for the user. Initially, the iterations of the toolkit prototype were built (4D Printing communicate toolkit prototype webpage). A comparative analysis revealed that while both groups relied on the image to communicate their design meaning, there were significant differences. Then, the toolkit was improved through experts' group interviews. Experts' interviews were done first in Chapter 4 (see Section 4.2) which the study aimed to obtain the opinions and experiences of the existing communication barriers. Then, the toolkit prototype development was based on the online surveys II results (see Section 5.4). In this chapter, experts from the British Standards Institution (BSi) and the Technical Product Realization (TPR) committee were interviewed to evaluate the concept communication framework for communicating the design process in 4D Printing.

6.5 Final design of the 4D Printing Toolkit Prototype

This section presents the final version of the 4D Printing communication toolkit prototype, which has been modified based on experts' evaluation feedback see Figure 88. A tooltip while hovering the box was added based on the feedback participants suggested. A tooltip is referred to as a text box or a graphical user interface element known as an *info tip,* or a hint is commonly used to provide info or a label of an element or feature. When hovering over a particular component or screen element, a text box will display information about that element. This prototype of the 4D Printing concept communication tool for 4D Printing is created to be used in the design process where designers and engineers can communicate to generate design ideas effectively.

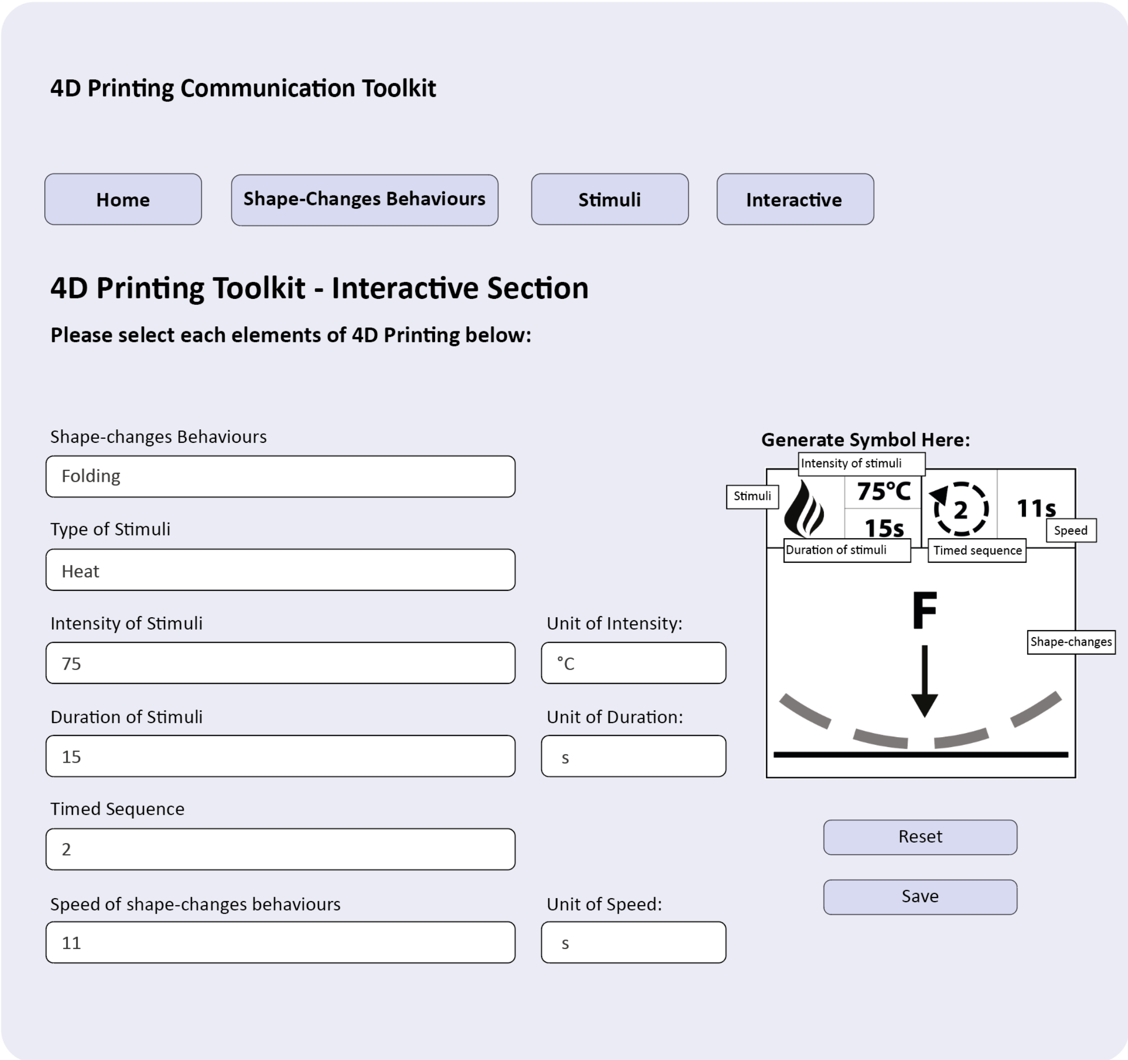


Figure 88. Example of the final version layout for 4D Printing toolkit (Interactive page).

6.6 Chapter Summary

The design toolkit was developed to extend the conceptual framework of the 4D Printing communication tool for the design process. As a result of creating a conceptual framework for the 4D Printing communication toolkit, designers and engineers will be able to work together and maximize the potential of this new technology. However, comments regarding design improvement have been taken to improve the usability and reliability of the proposed conceptual framework. The participants' feedback, such as adding a *tooltip* while hovering the element's box to provide user legibility that makes the elements possible to identify each. Participants suggested adding more elements to the symbol, such as material, pattern, and colour. The study accepted the feedback. However, creating a standardized symbol needs more time and consideration in the future work. The development of this communication framework is only a concept. It is the first step in more extensive research to improve communication and better understand the 4D Printing design process.

In conclusion, a communication framework for 4D Printing is necessary to ensure design representations are easily understood and recognized across different fields, from sketching ideas to technical drawing and CAD software. With the development of technology, there are an increasing number of communication methods for communicating the 4D Printing design process. The study hopes that the approach developed in this research can play a role and be helpful to designers and engineers to communicate and also induce more innovation in both 4D Printing processes and their applications in designing 4D Printing parts.

Chapter 7:

CONCLUSIONS

Chapter 7

CONCLUSIONS

Chapter content

7.1 Conclusion

This chapter concludes how objectives were met to answer the research questions defined at the beginning of the research process. It also provided details of the contribution (see Section 1.5), limitations and potential future work associated with this research. Within the chapter, the research objectives and the study's main contributions to the accumulative knowledge in the field of this PhD research. Different limitations associated with it and some suggestions and directions for future research are proposed and discussed in detail. The study's primary objective was to determine if the designers and engineers as a user could use the symbol to generate design significance to communicate effectively. The outcome of the research was to propose a communication framework for designers and engineers to effectively communicate the 4D Printing design process. The findings from the studies have an important implication for the communication in the design process of 4D Printed parts. The main conclusion that can be drawn is that the proposed concept communication framework can support users effectively and improve communication between designers and engineers during the design process and manufacturing.

7.2 Answering the Research Questions

The thesis investigated the communication barrier between designers and engineers in the 4D Printing design process. The main focus of the research presented in this thesis was to make contributions to knowledge about the 4D Printing design process by focusing on the communication barrier discipline by answering the research questions below through literature reviews and investigation by the empirical studies. Three research questions were formulated to fulfil the objective of this research. The research was conducted by various methods, such as surveys, interviews, and iterative focus groups. The results of the studies will be analysed to ensure that the research is valid and that the findings are accurate. In addition to the findings, the process will also be examined and evaluated to keep the research's reliability intact. The methods used in validating the validity of design theories are based on the principles of verification by acceptance and logical verification.

RQ1. What are the existing barriers between designers and engineers when communicating about 4D Printing?

The study revealed barriers regarding the communication of 4D Printing elements in the design process. These elements include explaining the shape-changing behaviour, stimuli and timed sequence of the 4D printing process. Through an empirical study, it was found that there was no standardized approach to communicating the 4D printing process on paper that was found in the focus group, which led to misinterpretation and ambiguous meaning. It was also found that there was no standardized method to use graphical symbols in CAD or line drawings to effectively communicate the 4D Printing process. These barriers have prevented designers and engineers from communicating the 4D Printing design process.

RQ2. What type of design representation is the most effective in communicating aspects of 4D Printing?

This research has explored the various aspects of communication and motivation. However, design representation has received less attention in 4D Printing technology. It is an important part of the design process as it can help generate and communicate design meaning [269]. In addition, representation helps the designer and engineer explore the various ideas and concepts presented in a design process. Results from the survey indicated that participants agree that graphical symbol representation is suitable and could help them effectively generate and communicate design meaning (see Section 5.5.3). In communicating 4D Printing through representation, the important part is to know the 4D Printing elements. Several elements in designing the 4D Printing process include shape changing behaviours, stimuli-responsive, timed sequence order, etc. (see Section 2.3.2 and 2.3.4). In this study, a graphical symbol is the design representation to communicate 4D Printing aspects. Graphical symbols do not rely on conceptual or visual connections to the entity they represent. Furthermore, they operate through conventions designed to help people understand the symbol's meaning (see Section 2.8.1). A graphical symbol is a visual representation that communicates a particular meaning to users (designers and engineers). In addition, this study proposed a communication toolkit that can generate the graphic symbol for 4D Printing so that designers and engineers can implement the toolkit in communicating 4D Printing through the actual communication tool such as CAD systems, Geometric Dimension and Tolerancing (GD&T), etc.

RQ3. How can the communication of 4D Printing between designers and engineers be improved?

Communication between designer and engineer is a two-way process in mutual understanding to improve communication in 4D Printing in the design process. 4D Printing technology is a technique that involves the design and manufacturing process. The relationship between designers and engineers is related to the design process, directly affecting manufacturing-related processes. In efforts to optimize the performance of the design process in 4D Printing, the researcher proposed a communication framework for designers and engineers to aid the 4D Printing design process. In contribution to knowledge, this thesis proposed the first communication framework for the 4D Printing design process. The 4D Printing conceptual framework aims to provide a communication toolkit that supports problem-framing to align designers and engineers with one solution for communicating in the 4D Printing design process, so they can start tackling the barriers in a collaborative and digestible manner based upon a shared vision. A contribution has been made to design research of the framework developed to create a communication tool for effective communication in 4D Printing. Following the guide from this concept of communication framework will ensure the success of the communication barriers (see Section 6.2.1). The development of the conceptual framework to communicate 4D Printing will reduce or eliminate many typical misunderstandings and missteps regarding the 4D Printing design process. Fluency of communication tools will enable effective communication between designers and engineers with clarity, accuracy and completeness in the design process of 4D Printing.

7.3 Strengths and Limitations of the Research

The rapid emergence and evolution of 3D printing technology have led to the development of a new research field called 4D printing. This new technology is still in its initial stages of development. Although it has many potential applications, it has some limitations that must be resolved to realise its potential fully. This section aims to summarise the strength and limitations of the research has been conducted in this thesis. The study was conducted to analyze the barriers that affect 4D Printing effectively communicating the design process.

This study has potential limitations and possible improvements which could be made. First, the limitation of this research is that the lack of attention had been given to directly related studies published in previous research on communication tools for 4D Printing. There is no specific research topic related to the communication tool for 4D Printing in communicating with the design representative or handling the design process. Finding research support or comparisons with the topic was challenging without much-related research. However, this can also be viewed as an opportunity for the researcher to investigate new research gaps in knowledge. Also, as for the specific concern regarding the participant selection from Brunel, researcher understand that this may introduce potential bias, and it is an important limitation to consider. The limited number of practitioners in the field of 4D printing might have constrained the ability to include a more diverse sample of participants, which could have influenced the generalisability of the findings and, this will be addressed in the future research.

Secondly, this study was the first attempt to develop the design representation communication for the 4D Printing design process. The second limitation of this study is regarding the aesthetic of the symbol design. The symbol is just a concept for the communication tool in this study. The study proposed a symbol to evaluate whether the design representation is a potential communication tool to communicate the 4D Printing design process effectively. The result can serve as a pointer to support the objective of this study, which symbol can be used as the representation communication tool in the 4D Printing design process.

The strength of this research was the evaluation of the communication tool with the British Standards Institution (BSI) and Technical Product Realization (TPR) committee. In creating design representation communication, expert guidance must be engaging and usable, and recommendations and suggestions must be taken from qualified decision-makers. As this study is the first attempt to create a communication tool for 4D Printing, it is important to get advice from the expert responsible for standardizing the design representation communication. The framework toolkit has been shown to the British Standards Institution (BSI) and Technical Product Realization (TPR) for the evaluation process, in which the proposed communication toolkit for 4D Printing received positive feedback regarding its recognition and usability. Once these limitations are resolved, 4D printing will become a revolution in creating new and efficient products by reducing the time it takes to design and manufacture process.

7.4 Recommendations for Future Work

This study has fulfilled the aims and objectives of the research. The main intention of this study is to investigate the communication barriers in the 4D Printing design process. In addition, this study explores the design representation to communicate and develops a framework as the potential support in the 4D Printing design process. The limitations outlined in this study are discussed further in this section as avenues for future work.

Further development for the aesthetic of the design representation *symbol,* which is more suitable for use in actual design. The symbol aesthetic requires further development to improve recognition and usability. The design representation should be simplified to be visually legible, complying with British Standards Institution (BSI) committee symbol standard design principles. Furthermore, improved symbols should go through the actual standardization process. Moreover, the proposed toolkit prototype design that contributes to the software development should be applied to CAD Software in the future.

Future studies will be conducted, including further development for the proposed communication framework with more comprehensive 4D Printing elements. In addition to the concept of the communication framework, this study defined the three main elements in

4D Printing: shape-changing behaviour, stimuli and timed sequence. Each of the elements is connected with the other. Furthermore, an interesting research area would be extending the framework to support other elements. Such as the type of materials used in 4D Printing, colour, more types of less commonly used stimuli, pattern, and size. It would be beneficial to identify more elements of shape change behaviour to optimize the application of 4D Printing technology.

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APPENDIXES

Appendix 1 – Letter of Approval: Interview

College of Engineering, Design and Physical Sciences Research Ethics Committee
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

17 January 2019

LETTER OF APPROVAL (CONDITIONAL)

Applicant: Miss Faten Ezrin Azhar

Project Title: 4D Printing

Reference: 15560-LR-Jan/2019- 17005-1

Dear Miss Faten Ezrin Azhar

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.
- Please agree with your supervisor how best to recruit the participants
- Start date has passed. Please be aware that under no circumstance can research activity involving human participants commence without ethical approval in place,

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to receipt by the Committee of satisfactory responses to any conditions that may appear above, in addition to any subsequent changes to the protocol.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Hua Zhao

Chair

College of Engineering, Design and Physical Sciences Research Ethics Committee
Brunel University London

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Appendix 2 – Letter of Approval: Focus Group

College of Engineering, Design and Physical Sciences Research Ethics Committee
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

6 February 2019

LETTER OF APPROVAL

Applicant: Miss Faten Ezrin Azhar

Project Title: 4D Printing Focus Group

Reference: 15796-LR-Feb/2019- 17592-2

Dear Miss Faten Ezrin Azhar

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to receipt by the Committee of satisfactory responses to any conditions that may appear above, in addition to any subsequent changes to the protocol.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Hua Zhao

Chair

College of Engineering, Design and Physical Sciences Research Ethics Committee
Brunel University London

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Appendix 3 – Letter of Approval: Survey

Brunel University London

College of Engineering, Design and Physical Sciences Research Ethics Committee
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

13 October 2020

LETTER OF APPROVAL

APPROVAL HAS BEEN GRANTED FOR THIS STUDY TO BE CARRIED OUT BETWEEN 13/10/2020 AND 29/09/2021

Applicant (s): MS fFATEN EZRIN AZHAR

Project Title: SURVEY-4D PRINTING

Reference: 25307-LR-Oct/2020- 28113-4

Dear MS fFATEN EZRIN AZHAR

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- **Approval is given for remote (online/telephone) research activity only. Face-to-face activity and/or travel will require approval by way of an amendment.**
- **The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.**
- In addition to the above, please ensure that you monitor and adhere to all up-to-date Government health advice for the duration of your project.

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to receipt by the Committee of satisfactory responses to any conditions that may appear above, in addition to any subsequent changes to the protocol.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Hua Zhao

Chair of the College of Engineering, Design and Physical Sciences Research Ethics Committee

Brunel University London

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Appendix 4 – Consent Form

4D PRINTING FOCUS GROUP CONSENT FORM

The participant should complete the whole of this sheet

Please tick the appropriate box

	YES	NO
Have you read the Research Participant Information Sheet?	☐	☐
Have you had an opportunity to ask questions and discuss this study?	☐	☐
Have you received satisfactory answers to all your questions?	☐	☐
Who have you spoken to?		
Do you understand that you will not be referred to by name in any report concerning the study?	☐	☐
Do you understand that you are free to withdraw from the study:		
• at any time?	☐	☐
• without having to give a reason for withdrawing?	☐	☐
• without affecting your future care?	☐	☐
I agree to my interview and activity being recorded.	☐	☐
I agree to the use of non-attributable direct quotes when the study is written up or published.	☐	☐
Do you agree to take part in this study?	☐	☐

Signature of Research Participant:

Date:

Name in capitals:

Witness statement

I am satisfied that the above-named has given informed consent.

Witnessed by:

Date:

Name in capitals:

Researcher name: Faten Ezrin Azhar	Signature:
Supervisor name: Dr. Eujin Pei	Signature:

Appendix 5 – Responses from Interview Data

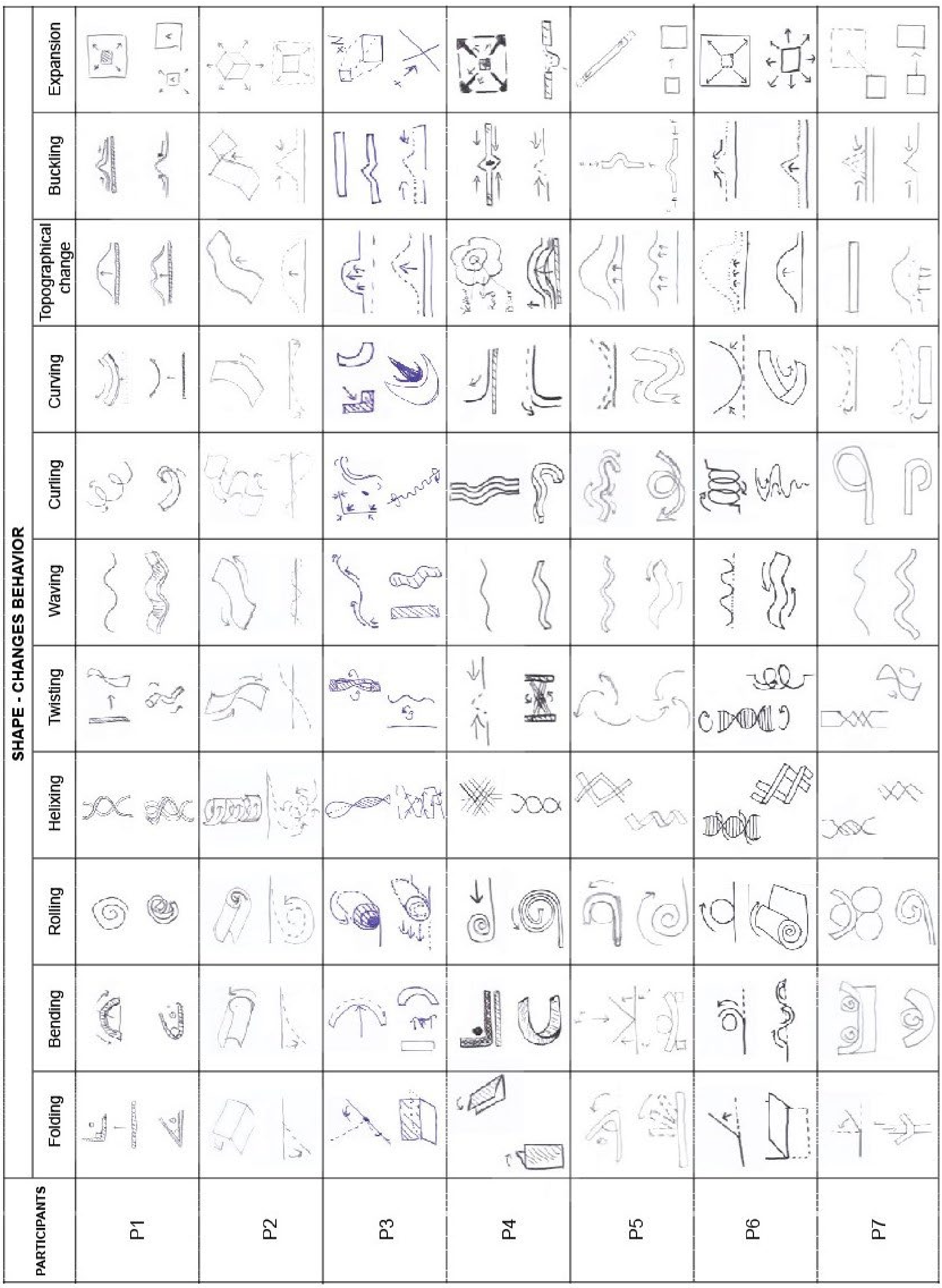
Questions	Participant	Responses from participants
Question 3 **How do product designers and manufacturing engineers communicate the use of 4D Printing?** *-What are the ways product designers and manufacturing engineers communicate the use of 4D Printing when creating a product?*	P-SL	I believe product designers and manufacturing engineers communicate the use of 4D printing by emphasizing its efficiency when creating products with moving parts. Actuating parts and automated actuating parts require a lot of resources and components: power storage, hinges, pins, sensors, on-board processors, and motors. Smart materials and 4D printing allow these requirements to be embedded into the material itself. This would reduce the amount of parts, reduce the weight, reduce manufacturing costs, and simplify the design. It also allows for the materials to react to their environment without the need for complex and expensive systems.
	P-SWN	Product designer use to necessary skills such as sketches, 2D drawings, 3D CAD modeling and material renderings to communicate with engineers. Currently, their communicate are delivered via 3D modeling tools such as CAD / CAM / CAD.
	P-HWM	As far as I can tell, at this moment, 4D printing is still mostly in the cradle stage. Need more time to become more mature and get ready for real applications.
	P-MM	Case Study
	P-RPH	Manufacturing
	P-ZO	Real communication
	P-GLHH	Through website or journal that designers and engineers can share and change knowledge about 4D Printing.
<u>Question 4</u> **How do product designers and manufacturing engineers apply the use of 4D Printing to product?** *-product manufacturing, product development or product design.*	P-SL	The design of 4D printed products can be quite complex, especially if you have multiple moving parts in a single product. Designers must think about the path of shape change for each individual actuating part: will this moving part interfere with this moving part? How can I control the rate of shape change for this part? How do I control the limit of a parts shape change? Other factors that must be accounted for are what material are being used, what is the activation method, what is the size and weight of the part, the time it takes for activation (seconds, minutes, hours), what is the environment of the product and will it affect the shape change properties, and is the shape change process reversible. Once these factors have been addressed then the designer can start their

		design of the 4D printed product. Next, for development and manufacturing, engineers have to ensure that the static materials and shape changing materials are compatible and will not delaminate after printing. Engineers would also need to investigate the type of 3D printing method (FDM, polyjet, stereolithography, SLA, etc.) and decide if they are compatible with the shape changing materials. Next, engineers decide if the 4D printed product saves time and resources during the manufacturing process. Reducing the number of parts required to create moving parts could save money and resources, along with time for assembly of these parts.
	P-SWN	I really considered it. But I can't make answer because actually, 4D printing technology is in its infancy, I think it is still difficult to develop 4D printing products yet. I just know that few experiments of 4D Printing to product for example, recent real applications are smart valve (Bakarich et al, 2015) and Shape-Shifting Pasta (Wang and Yao, 2017).
	P-HWM	Right now, prototype is still the major role for 4D printing.
	P-MM	Application - Specific software
	P-RPH	Reliability part, improve the material by make development of material, stimulation
	P-ZO	Specific software. Journal and report 4D Printing.
	P-GLHH	Specific software
<u>Question 5</u> **What are the existing barriers between product designers and manufacturing engineers when communicating about 4D Printing? Or 3D Printing**	P-SL	I think the main barriers are integrating large crazy ideas that can come from designers with the practicality of manufacturing. This depends on a large amount of communication between the designers and engineers. Communicating what does not work and reiterating those design changes. Also, the technology is very new to both designers and manufacturers. So, a lot of trial-and-error might occur. However, this is can be said for most product design and not just 3D/4D printing. 3D printing can speed up the process of designing to prototyping. Designers can come up with ideas, send those designs to manufacturers, 3D print those prototypes, and relay the design changes to designers in a short time.
	P-SWN	Type of CAD tools have limitations to express their requirements of product applied in 4DP technology which will shape deformation by external stimuli. And also testing.

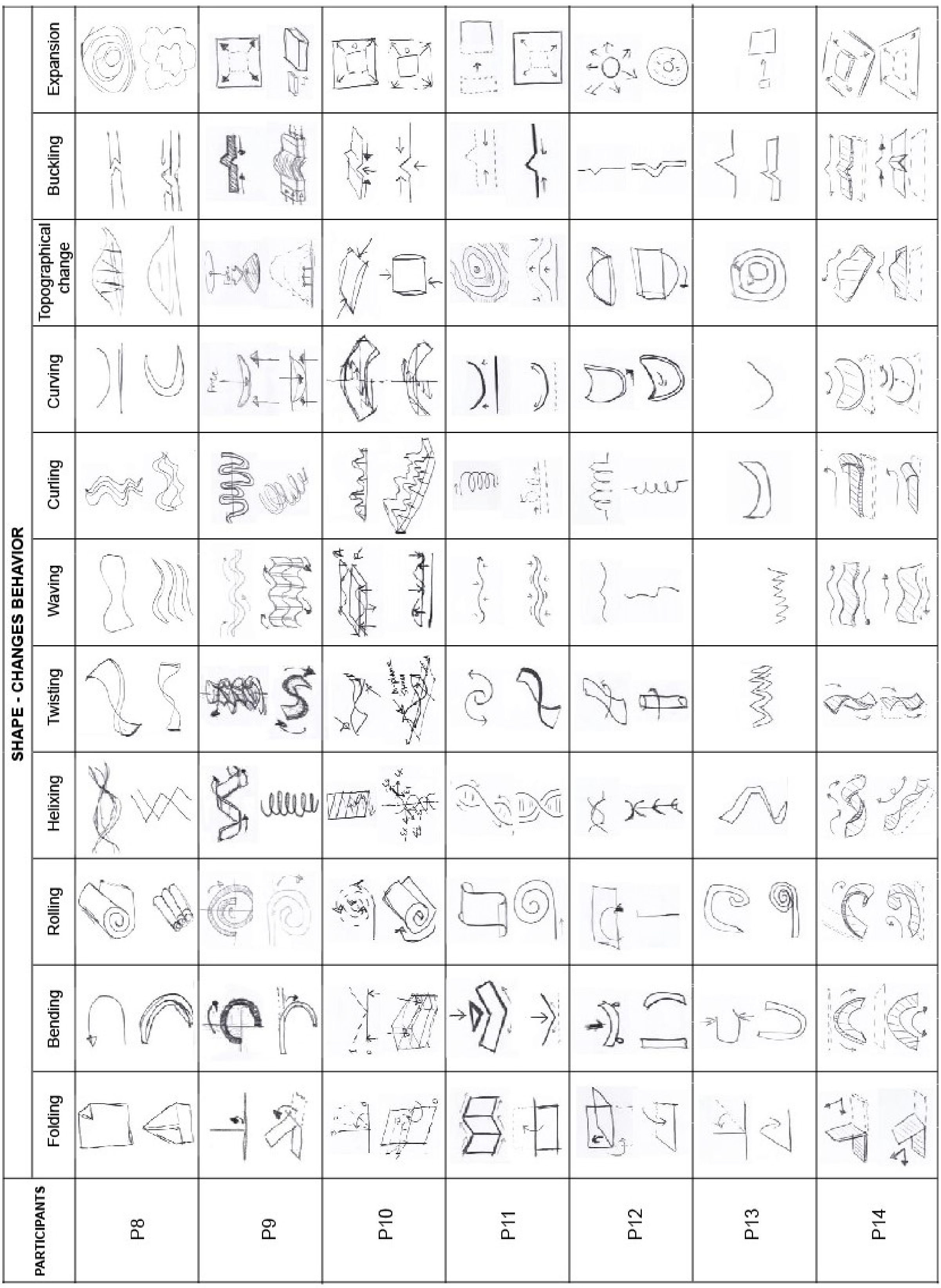
	P-HWM	There are many new design concepts in 4D printing and the technologies are different from conventional approaches and sometime difficult to use for product designers and manufacturing engineers. More R&D is required.
	P-MM	Challenge in the process. Engineers have knowledge of materials more than designers but limited option.
	P-RPH	When spreading about 4D Printing
	P-ZO	By create framework as a guideline. Technical issues. Language. Lack of interest.
	P-GLHH	Type of material used.
<u>**Question 6**</u> **What type of design representations/ tools are the most effective to communicate aspects of 4D Printing?** *-What is the available/existing design tools to communicate and applicable for 3d printing?* *-What is the limitation, and how to improve it?*	P-SL	Another issue is the limited modeling and simulation for 4D printing and its shape changing materials. Designers can create elaborate designs for shape changing products, but there is limited software that can predict the shape changing patterns of those materials. Due to this, a lot of 4D printing design might be trial and error. Engineers should take their time to study many different shape changing materials, the material properties that affect shape change, and the environment/activation method that affects the shape change. These properties should be included in the software so that users can select a shape changing material for a 3D model and simulate its shape change before it's 3D printed. Currently, the most common 3D modelling software is Solidworks and Creo parametric, but they do not have a shape change simulation. Skylar Tibbits, MIT, used Autodesk Cyborg that had the ability to input material settings in order to predict the movement patterns of 4D printed materials.
	P-SWN	Various CAD modeling and simple prototype directly
	P-HWM	For 3D modelling par, there are a lot of commercial software. For shape switching, compliant mechanism may be simulated by FEM for simple designs, but for shape memory based, it is still a challenge.
	P-MM	Experiment. Prediction of final product.
	P-RPH	Stimulation 3D Printing imitation shape.
	P-ZO	Real concept and clear needs
	P-GLHH	CAD Software such as Solidwork.
<u>**Question 7**</u>	P-SL	I believe 4D printing would require a strong team of mechanical, materials, chemical, manufacturing, and software engineers. The

How can the communication of 4D Printing be developed or improved between product designers and manufacturing engineers? *-Do any of these methods or representations can be applied to 4D Printing* *-How can you vision this to apply to 4D Printing*		teams should take advantage of project management tools and try to create parallel material studies. Designers should communicate the purpose/application of the 4D printed product, its final design, material, size, and manufacturing method. Manufacturing engineers should suggest changes in reference to the 3D printing method, the material used, activation methods, and the shape changing properties to the designers and engineers for the most efficient 4D printed product. Testing and design protocols should be made for best repeatability results.
	P-SWN	I think it will be the hardest part of the time notion. It will be difficult to deliver the movement of 4D printing objects that the designer thinks to the engineer because of the time difference that they imagine. Unlike conventional motion implementations, motion using material properties instead of structures will be more difficult to predict.
	P-HWM	Need both side to spend time to find the right applications first and then work out a way to realize them. But need reliable and easy to access software. With reliable software for 4D printing, we can see some great applications in future.
	P-MM	4D Printing still new. No tools actuated yet for final shape.
	P-RPH	4D Printing still new. No tools actuated yet for final shape.
	P-ZO	Capabilities in manufacturing and share new material.
	P-GLHH	By technology development.

Appendix 6 – Results from Focus Group II



Appendix 6 – Results from Focus Group II



Appendix 7– Experts Interview: British Standards Institution (BSI) and Technical Product Realization (TPR)