Investigating the Communication of 4D Printing among Product Designers and Manufacturing Engineers

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ABSTRACT
4D Printing involves the use of 3D Printed objects that can self-assemble or transform using smart materials. This research is to find out how marks on paper through the use of sketches are communicated to represent the process of 4D Printing. In this research, quantitative and qualitative methods through interviews and focus groups will be used to acquire data on how product designers and manufacturing engineers communicate the process of 4D Printing. The findings from the focus group activities showed that while there were a diverse range of 'sketches' produced, colours were used to indicate the parts and materials, while arrows were used to indicate the folding sequence, and symbols were used to indicate the process of time.

KEYWORDS: 4D Printing; Communication; Computer Aided Design; Product Designer; Manufacturing Engineer

1. INTRODUCTION

According to the Merriam - Webster Dictionary, a designer is a person who creates and executes plans for a project. When comparing products of the past with those of today the main difference is that the tools, machines, materials, processes and systems are now far more advanced and in particularly suited for mass production Morelli, (2002) highlighted that product designers traditionally sketches, models and Computer-Aided Design (CAD) to create the outcomes necessary for the final product. For these reasons, product designers have to acquire a broad range of skills and experience in order to communicate, relating and work with people in a multi-disciplinary setting to provide solutions. These sketches play an integral part of analytical computations, where they can be used to present and define the characteristic parameters of the product. Communication tools such as sketches and CAD are used to convey information with technical and non-technical individuals throughout the design process (Rose, 2005). Therefore, choosing the right and most effective medium for communication can be seen as a key element and a factor of successful product development for product designers and manufacturing engineers (Goodman and Truss, 2006; Barbarash, 2016). Today, the use of Additive Manufacturing (AM) which is also known as '3D Printing' or 'Rapid Prototyping' (Mueller, 2012) is seen as a popular tool which can be used to produce prototypes or end-use parts. AM is a process where tangible artefacts are produced based on a digital model through the process of material deposition layer by layer. Taking a step further, 4D Printing is a process in which 'time' is the fourth dimension where bi-stable Additive Manufactured structures can be programmed to transform into a secondary shape using 'stimuli' responsive materials' (Pei et al, 2017).

2. EMPIRICAL RESEARCH

The overall aim of this research is to understand how product designers and additive manufacturing engineers communicate in order to fully utilise the potential of 4D Printing. By doing so, researchers and practitioners will gain a better understanding of communicating more complex forms of shape change behaviour. Before collecting the data from the participants, approval from the Brunel Research Ethics Online (BREO) was sought to receive endorsement before commencing the interviews and focus groups. The purpose of the ethical approval process is to ensure research integrity and so that the respondents understand the information given will be kept secure and confidential.

2.1 Interviews

The use of interviews have been recognised to be one of the best and most successful methods for collecting data from participants (Alshenqeeti, 2014). The sample size is typically small and respondents are selected to fulfil a given quota based on the amount of time and resources given. The targeted respondent should have an adequate knowledge to accurately provide sufficient feedback for the researcher. For this research, semi-structured interviews were chosen to allow the interviewer to gather more information. The interviewees were selected from those active in the field of design and engineering and familiar with the overall 4D Printing design process. In total, eight respondents were selected for the interviews which were conducted face-to-face and over a Skype call. 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.

2.2 Focus Group Observation

In addition to interviews, three separate focus group sessions involving a total of six participants were recruited. This involved three design PhD students and three engineering PhD students studying at Brunel University London. Within each focus group, one participant acted as the designer and the other was the engineer. The designer was asked to communicate three separate tasks that involved the direction of folding, the timed sequence of folding, and the speed of the shape change behaviour. These were the three main elements in the 4D printing process which were critical for the shape change effect (Pei et al, 2017). The engineer was supplied with three 3D Printed parts which were used as props. The researcher acted as a silent observer and took note of the activity throughout the process. The entire activity took about one hour long for each focus group. As mentioned, the focus group activities were supported with the use of 3D Printed props as a representative of the 4D Printed effect as shown as figure 1a, 1b and 1c below. The direction of folding was being represented in Figure 1a, the speed of the shape change behaviour being represented in Figure 1b, and the timed sequence of folding being represented in Figure 1c.

Figure 1a: (Object 1)

Figure 1b: (Object 2)

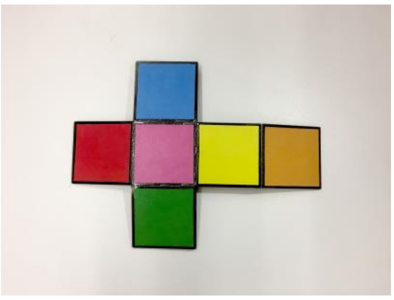


Figure 1c: (Object 3)

2.3 Limitations of this study

For this study, there were several limitations that could have impacted on the findings. It is important to note that the interviewed participants had a diverse range of backgrounds (PhD students, experts, practitioners, designers and engineers) and they also had different levels of knowledge and skills. Although over 80 potential subjects were contacted, unfortunately only 10 percent had agreed to be interviewed. In some instances, some interviewees initially agreed to participate, but later withdrew when they were asked to provide their signature for consent as part of the University research ethics concordat. They had reservations about providing their signature and one reason could be that they are not familiar with the system in the UK. Another limitation related to empirical data gathering was about finding suitable number participants who had 4D Printing expertise and were prepared to actively take part as subjects for the focus group activities the focus group activities. Although six participants were recruited, the initial observations showed that some participants had reservations and seemed to have hesitation about demonstrating their sketch skills.

3. ANALYSIS AND RESULTS

According to (Miles et. al. 2014) interview results become purposeful and have meaning only after the data has been analysed. Clustering and descriptive coding is a method that is used by researchers to annotate and assign labelling in order to summarize given information. At the same time, or focus group activities, observational methods may be characterized by their degree of formality, based on the level of structuring of the observations and recording methods, and their intended use. The first question asked, participants about "their professional background" and three subjects indicated that they had recently engaged in this 4D Printing research area. Five of them claimed that they were more familiar and had experience in this area of research for many years. For the second question, participants were asked to "further describe their experience in 4D Printing". Four of the participants mainly used SMPs (Shape Memory Polymer) in their work in order to experiment with different shape changing properties and their behavioural effects. Three more participants claimed that their work was focused on SMEs (Shape Memory Effect) using stimuli to generate the shape change through a series of heating and cooling experiments. The third question asked the participants about "how product designers and manufacturing engineers communicate the use of 4D Printing" Four respondents implied that they communicated using the context of the application; and the remaining four respondents implied that they communicated using the context of the choice of material when creating a product. The choice of material indicated how the 4D Printing effect would work as well as its intrinsic properties. The next question asked "how product designers and manufacturing engineers apply the use of 4D Printing to products". Three of the participants said that they did this by identifying a suitable framework to describe the product using relevant literature or by experimenting and analysing 'case studies. Five others considered the use of database 'applications' by building a knowledge repository of 4D Printing to assist product designers and additive manufacturing engineers in heuristic decision making.

When asked about "what are the existing barriers between product designers and manufacturing engineers when communicating about 4D Printing", two participants claimed that CAD software was the barrier; while three participants claimed that the understanding and selection of materials was the barrier; and the last three participants claimed that technologies involving a lot of trial and error was also a barrier. When asked about "what type of design representations or tools are the most effective to communicate aspects of 4D Printing", three respondents claimed that it was important to be able to evaluate the 'experiment' in relation to some type of conceptual understanding; and five others responded that CAD tools if correctly implemented, could greatly facilitate the design process. Finally, when asked about "how can the communication of 4D Printing be developed or /improved between product designers and manufacturing engineers", four of them claimed that technology development with new approaches, and three of them claimed that new methods of communication, as well as one person citing at new forms of software could help enhance communication between product designers and manufacturing engineers. For focus groups, the designer (Participant A) had to follow the instructions given by the researcher and to sketch the intent on paper without speaking or any verbal means of communication. Participant B being acted by an engineer, was asked to view the sketches made by Participant A and to then use the props and act out how the object would fold in a particular direction, through timed sequence and speed. Figure 4a, 4b, 5a, 5b, 6a, and 6b showed evidence of the participants during the role play activities in the focus groups. Results from the observations showed that the marks made on paper could give unpredictable and spontaneous forms of communication.

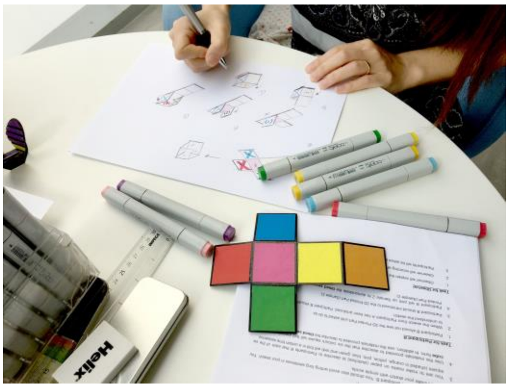


Figure 2a : Participant A (1)

Figure 2b : Participant B (1)


Figure 3a : Participant A (2)


Figure 3b : Participant B (2)

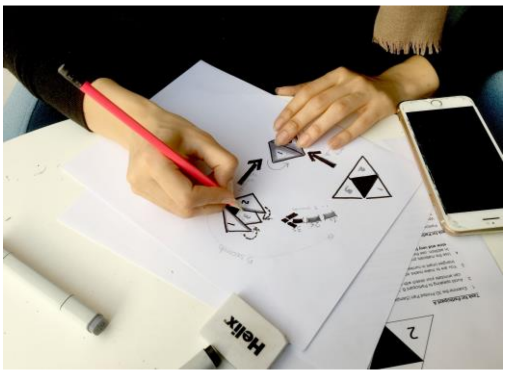
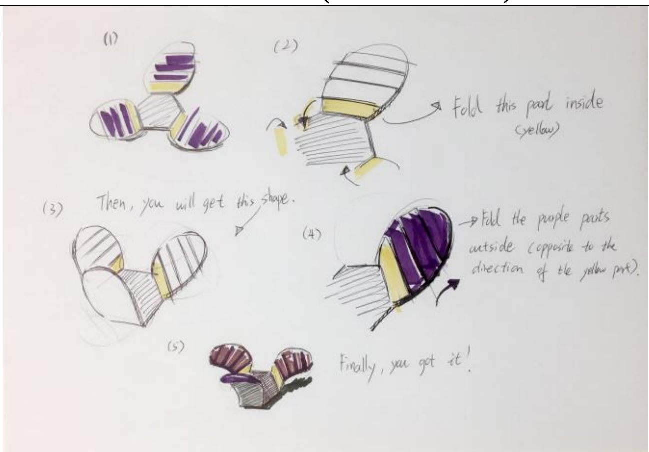
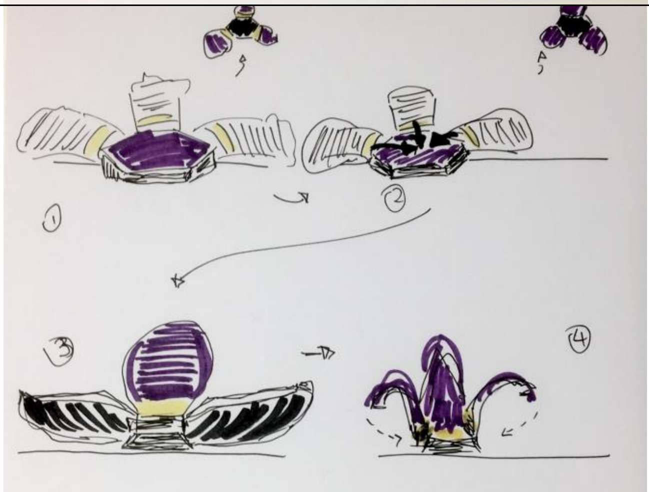


Figure 3a : Participant A (3)


Figure 3b : Participant B (3)

Table 1 showed that all participants give instruction using 'arrows' to indicate the steps needed to fold the 3D Printed sample. In the second activity shown in table 2, it can be seen that participants A1 and A2 have both used 'numbers' to indicate the 'timed sequence' to represent the steps and process. However, participant A3 only used 'arrows' and 'colours. Lastly in table 3, the participants used 'colours' and 'shading' to differentiate the surface. Participant A1 used green colours to represent flat surfaces. Red lines were used for the folding action and blue lines for closing action. For Participant A, time was indicated using 'symbols' and splitting this into two separate sketches to define the differences in speed.

ACTIVITY 1 (DIRECTION)	NOTES
	Participant A1 • Step by step approach. • Arrow to indicate direction and fold. - Indication arrow to point.

	Participant A2
	
	• Step by step
	• No words
	• Type of arrow
	  - Dash line arrow
	  - Thick black arrow
	  - Long arrow
	• Show two views (top and side)

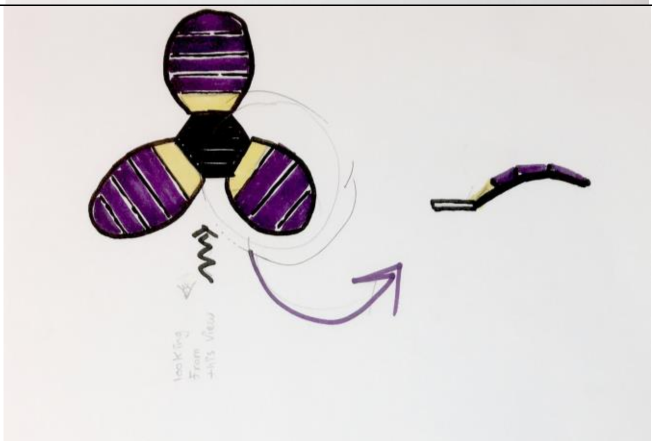
	Participant A3 • Arrows used commonly - Wiggly line arrow • Line weight for selection • Symbol for view angle

Table 1 : Activity 1 required participant A to describe the **direction** of change.

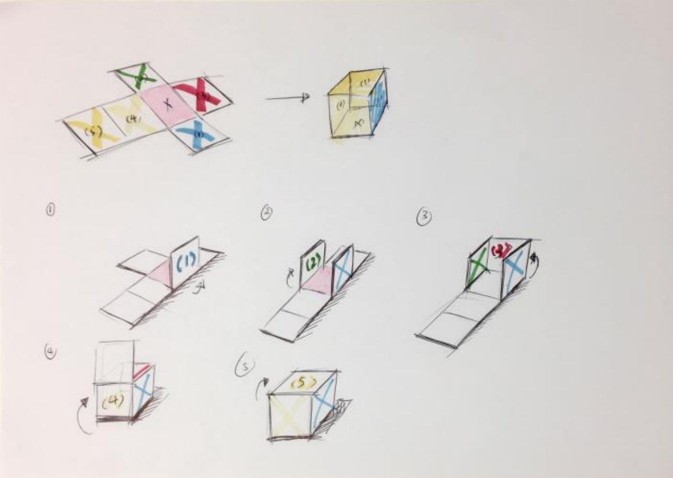
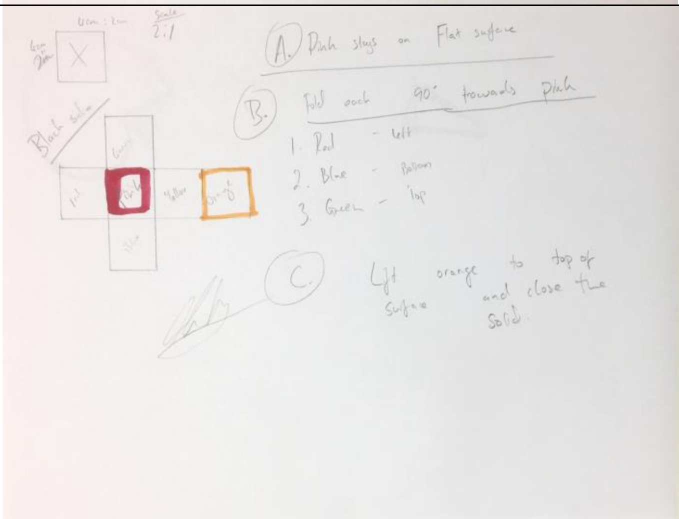
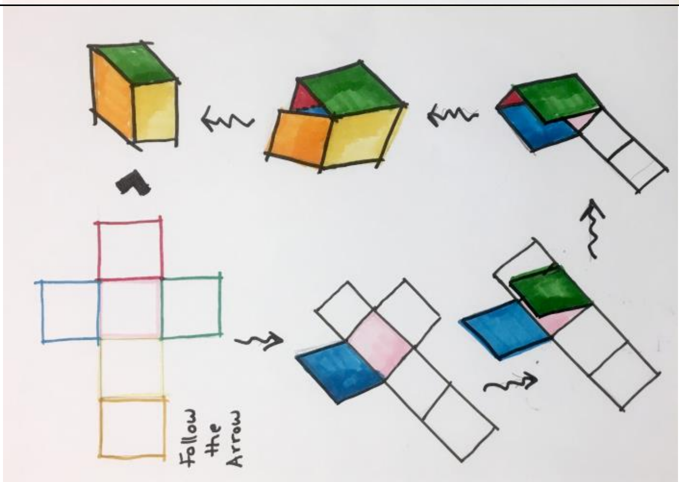
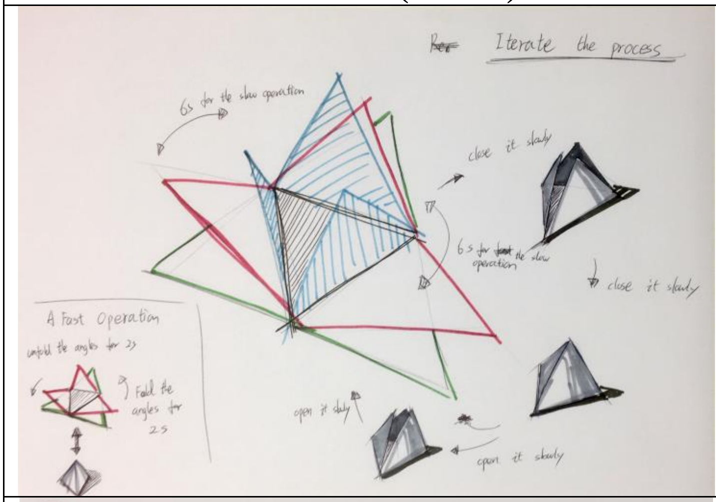
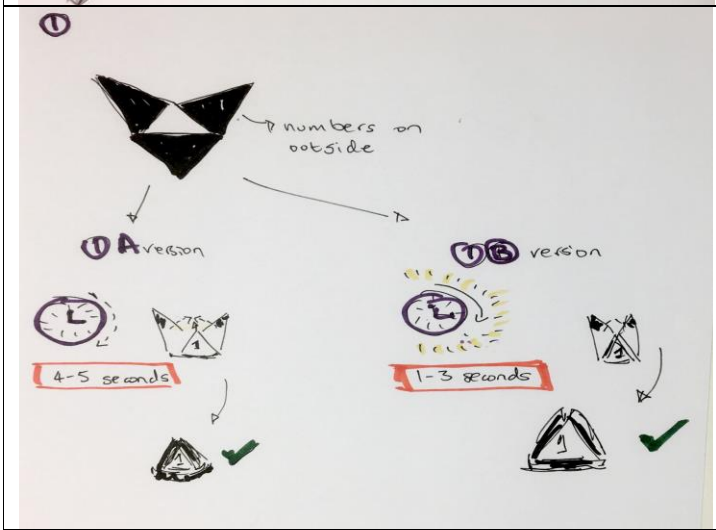
ACTIVITY 2 (TIMED SEQUENCE)	PARTICIPANT
	<u>Participant A1</u> • Showed labelling of sides • Showed step by step guide • Used colour to represent sides • Used number to indicate process • Used arrows to indicate fold
	<u>Participant A2</u> • Tried to write words to explain steps • No arrows • Colour to indicate side
	<u>Participant A3</u> • Two types of arrows • Colours to represent side • Arrows to explain steps

Table 2: Activity 2 required participant A to describe the **timed sequence** of change.

ACTIVITY 3 (SPEED)	PARTICIPANT
	Participant A1 • Shadings and colours to differentiate different surface • Wrote ‘6s’ to represent slow speed. • Wrote ‘2s’ to represent fast speed. • Used lots of words
	Participant A2 • Wrote A and B versions • Highlighted speed in red box • Timer symbol was used • Ticked symbol meant the end of the finished process

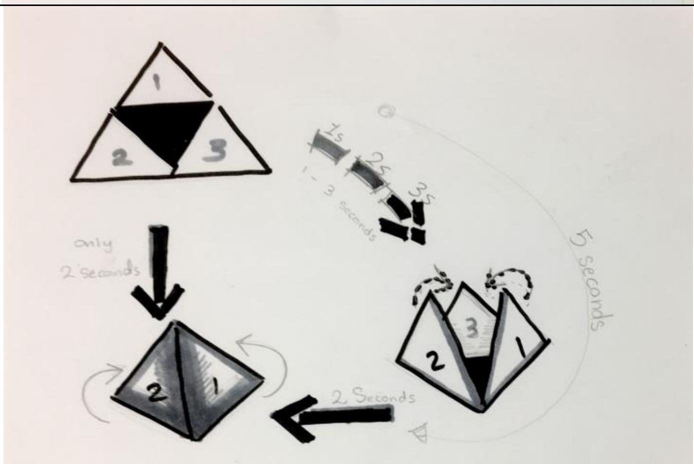
	Participant A3
	
	• Only black and white was used
	• Indicated time
	• Used different types of arrows
	  - Bold arrows
	  - Folding arrows
	  - Arrows to represent process

Table 3: Activity 3 will require participant A to describe the **speed** of change.

4. CONCLUSIONS

The aim in this research was to focusing on how product designer and additive manufacturing engineer understand of reciprocal communicate with each other by using mark on paper. By conducting focus group activities, the experiments consisting of video observation and semi structured interviewed question were carried out with six doctoral degree students at Brunel University. The conclusion of this research paper will analyse what has been studied.

Empirical studies on communicate using mark on paper need to be develop and suggest improvement. This research will give benefits to product designer and additive manufacturing engineer to communicate each other in applying 4D Printing on products.

5. REFERENCES

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Appendix 1 – Responses from Interview Data

Respondent	Question No. 3	Question No. 4	Question No. 5	Question No. 6	Question No. 7
Participant 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.	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	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.	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	I believe 4D printing would require a strong team of mechanical, materials, chemical, manufacturing, and software engineers. The 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.

		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.		material settings in order to predict the movement patterns of 4D printed materials.	
Participant 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.	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).	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.	Various CAD modeling and simple prototype directly	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	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	Right now, prototype is still the major role for 4D printing.	There are many new design concepts in 4D printing and the technologies are different from conventional approaches and sometime	For 3D modelling par, there are a lot of commercial software. For shape switching, compliant mechanism may be	Need both side to spend time to find the right applications first and then work out a way to realize

	and get ready for real applications.		difficult to use for product designers and manufacturing engineers. More R&D is required.	simulated by FEM for simple designs, but for shape memory based, it is still a challenge.	them. But need reliable and easy to access software. With reliable software for 4D printing, we can see some great applications in future.
Participant P-MM	Case Study	Application - Specific software	Challenge in the process. Engineers have knowledge of materials more than designers but limited option.	Experiment. Prediction of final product.	4D Printing still new. No tools actuated yet for final shape.
Participant P-RPH	Manufacturing	Reliability part, improve the material by make development of material, stimulation	When spreading about 4D Printing	Stimulation 3D Printing imitation shape.	4D Printing still new. No tools actuated yet for final shape.
Participant P-ZO	Real communication	Specific software. Journal and report 4D Printing.	By create framework as a guideline. Technical issues. Language. Lack of interest.	Real concept and clear needs	Capabilities in manufacturing and share new material.
Participant P-GLHH	By website or journal that designers and engineers can share and change knowledge about 4D Printing.	Specific software	Type of material used.	CAD Software such as Solidwork.	By technology development.