



Understanding and classifying the role of design demonstrators in scientific exploration



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ABSTRACT

This paper describes the development of a model for classifying the different type of ‘design demonstrator’ that might be used in translating scientific activity from the laboratory to the market. Two detailed case studies are described in which designers worked closely with scientists. In one of the projects, the scientists were seeking to commercialise their research. In the other, the research was at an early stage and the scientists had not considered commercialisation. Different types of physical artefact produced in these collaborative projects were analysed to identify the extent to which they might contribute to science, technology, application or market. Evidence indicates that demonstrators might fulfil multiple purposes and that the translation from science to market is more complicated than is often shown in linear models. An original classification of the role of demonstrators through this journey is provided.

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1. Introduction

There is evidence to suggest that the early involvement of industrial design expertise in the development of new technology can improve its potential for future application (e.g. Kotler and Rath 1984, Lorenz 1994, Black and Baker 1987, Roy 1999, Gemser and Leenders 2001, Hertenstein et al., 2001). These studies report explicitly on the development of technology in industrial settings, which is characteristically driven by commercial goals. However, despite compelling evidence for the value of designers in industry, there has been surprisingly little work exploring the potential impact that design might have on scientific research in academia.

There need to explore this in more detail is both important and timely due to the growing emphasis placed on ‘impact’ of research in the UK¹, EU (Fisher et al., 2009) and internationally. In the UK for example, the government spends in the region of £2.5bn on R&D (ONS 2012), but is acknowledged as being weak in translating its strong science base into innovative companies or products (Livesey et al. 2006). The well-known term ‘valley of death’ is often used to describe the difficulty of progressing scientific discovery from laboratory to market. This concept was first coined by Merryfield (1995), referring to the transfer of agricultural technologies to the third world but has since been adopted as a metaphor to describe the hurdle that exists between primary research and the

commercialisation of new products (Markham et al. 2010). Increasingly, the ‘valley of death’ is used to refer to a resource gap in moving ideas from laboratory to market. The 2005 Cox Review noted that “technology that is not carried through into improved systems or successful products is opportunity wasted” (Cox 2005).

A common explanation for this is a “cultural gap” between the scientists, whose mission is to understand fundamental principles and the more commercially oriented development specialists, whose goal is to introduce new products (Markham 2002). One route to addressing this issue is to “manifest the discovery as a product”; designers are noted as providing a key ‘interface’ role (Boren et al. 2012) to enable this.

However, although much is known about the role of design in industry, little is known about the potential role that designers can play in supporting the development of new science in an academic setting as a route to bridging this valley-of-death.

The 2007 Sainsbury Review highlighted how “the use of design helps scientists to develop commercial applications for their work while it is still at the research stage or at the outset of the technology transfer process” (Sainsbury 2007, p151). Evidence for this assertion came from a pilot scheme, run in partnership between the Design Council, the Engineering and Physical Sciences Research Council (EPSRC) and University College London Ventures to bring design consultancies into scientific research (Design Council, 2006). A follow-on study conducted in 2009 saw a number of consultancies paired with Technology Transfer Offices (TTOs) from several of the UK’s leading universities (Design Council, 2009). These consultancies provided design mentoring to scientific

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¹ <http://www.epsrc.ac.uk/funding/howtoapply/preparing/impactguidance/>

teams. Participants in these studies reported several benefits of working with designers. In both the 2006 and 2009, the participating scientists were already seeking to commercialise the results of their work, and so had conceptually already started to cross the valley-of-death.

Rust (2004, 2007) has also commented on the potential benefits and barriers to designers working with scientists and discusses how these barriers might be overcome. Such benefits of engaging designers in the scientific process include: Speeding up the process of commercialisation; Bringing a perspective of potential users and the market place; Raising awareness of future applications; Making scientists aware of the process of commercialisation; Helping to communicate ideas between research collaborators and potential investors in an exciting and credible way; Visualising scenarios of use. Prototyping for quick testing of ideas; Producing artefacts to aid understanding and stimulate ideas; and Assisting with communication and dissemination of research. However, the data set supporting these assertions is not clear and so their validity cannot be easily evaluated.

Building on these themes, Driver et al., 2011 conducted a study in which designers worked closely with scientists to identify the critical contributions that designers might make. These included: Prototyping for quick testing of ideas; Challenging scientists' perceptions; Applying scientists' underlying theories; Creating artefacts to aid understanding and stimulate ideas; Assisting with communication and dissemination of research; Visualising scenarios of use; Creating technology demonstrators; Producing devices/processes/spaces to enhance scientists' research capability; and Performing user and market research to enhance the commercial potential of the outputs of scientific research.

A common theme running through the findings from Rust, Driver and the Design Council is the role of designers in creating visualisations, prototypes and tangible artefacts which serve to support communication, build understanding and enable testing of ideas.

But, despite these initial observations, there is little empirical evidence on the specific role that design demonstrators might play in supporting the transition of scientific activity towards commercialisation. Thus, this research seeks to address the question: *what are the roles of 'design demonstrators' in supporting the transfer of technology from the laboratory to the market?*

This research is motivated by a deep knowledge of the skills and abilities of the designers on behalf of the research team and a belief/hypothesis that there would be significant benefits should designers be more systematically and involved in scientific activity.

This paper is structured as follows:

- Firstly, there is a short review of literature relating to 'boundary objects', or artefacts which help mediate in the boundary between actors with different perspectives, knowledge, skills, locations or status in social systems. This highlights the potential for designers as creators of visual objects and demonstrates that no prior work has explicitly studied this phenomenon in the progression of scientific activity towards commercialisation.
- Next, standard models that describe the progression of science from lab to market are presented. The rationale here is that typically, demonstrators are viewed as technological prototypes which are close to market. By considering the broader development space, it is possible to explore the potential for other types of demonstrator. Specifically, this section explains the choice of the 'Science, Technology, Application, Market' (STAM) model which is used as a basis for analysis of case data, in order to position the various types of design demonstrator produced in the case studies.

- This is followed by an overview of an empirical study in which designers worked along scientists with the express intention of supporting the translation of technology towards application or market.
- Two case studies are then described in more detail in which the nature of the design demonstrators produced is explored.
- Finally, the paper will present an original classification of design demonstrators, built from insights generated from the case studies and literature.

2. Demonstrators, prototypes and boundary objects

Artefacts as mediators between actors in a social system have long been discussed as 'boundary objects'. Star (1989) and Star and Griesemer (1989) are accredited with first describing this concept, in the context of scientific collaborations, between scientists with disparate knowledge domains. They described 'boundary objects' as "(...) an analytic concept of those scientific objects which both inhabit several intersecting social worlds (...) and satisfy the informational requirements of each of them. ... they have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation." (Star and Griesemer, 1989: 393).

This basic concept has subsequently been adopted in scholarly discourses in a wide range of disciplines, including: organisational studies (e.g. Zeiss and Groenwegen, 2009); engineering (Henderson 1991); and New Product Development (Carlile 2002). Other terminology has also been adopted, including 'intermediary objects' (Vinck 2009, 2012) which act as translators or mediators between actors in an actor-network system. Ewenstein and Whyte (2009) discuss visual representations in architectural design as epistemic (or knowledge) objects which are 'abstract in nature; objects of enquiry and pursuit ... characterised by lack of completeness' (p. 9). Common to all of these is the notion that boundary objects can assist in creating common knowledge among individuals in dispersed design teams and across boundaries (Carlile 2002, 2004).

In engineering, it is especially in the field of innovation, new product development and design that this concept is discussed. Henderson (1991, 1998) adopted this concept in an ethnographic study of design activities, recognising that the world of designers is inherently visual and related to material experiences. For designers, sketches, drawings and other visual representations are "the building blocks of technological design and production ... Moreover, because they are developed and used through interaction, these visual representations act as the means for organising the design to production process, hence serving as a social glue between individuals and between groups" (Henderson, 1991: 449). Henderson established that design meetings typically centre around, on and through these visual representations.

Bechky (2003) and Siedel et al. (2014) both determined that not all objects are effective in spanning boundaries. For example, Bechky (2003) claimed that some objects (e.g. CAD drawings) may not facilitate the creation of 'common ground' between actors, especially where the language expectations of participants is very different. Siedel et al. (2014) note that prototypes "did not always help teams coordinate their interdependent work" (p700) and as a result, they describe the notions of concept 'coherence', where concepts generate shared understanding, and concept 'disunity' reflecting a lack of common understanding.

It has been claimed that objects are most effective at facilitating communication when they are generated collaboratively (Terwiesch and Loch, 2004) where prototypes help to mediate between the different objectives and motivations. Bogers and Horst

(2013), explored collaborative prototyping, in the setting of a technology based firm and showed that prototypes can help create a climate of problem solving and collaboration across functional, organisational and hierarchical boundaries. They specifically distinguish between ‘designer’ and ‘managerial prototyping; the former enabling rapid iteration, but requiring technical expertise and the latter is more superficial but enabling wider participation.

Designers are clearly recognised as having value in collaborative activity, due to their ability to visualise and think through prototypes and sketches (Brereton and McGarry, 2000). Hargadon and Sutton (1997) explored innovation in an international design firm, and showed that designers might act as technology brokers, due to experience in working across multiple technology fields. Thus, they are able to transfer ideas and concepts between these technology domains. Nicolini et al. (2012) present one of the few studies exploring boundary objects in a scientific research setting. They concluded that interdisciplinary interactions and collaborations form around and are mediated by boundary objects (p. 616), which can facilitate both mundane infrastructural support (e.g. emails) as well as work across boundaries (e.g. presentation slides).

In summary, there is a wealth of prior work that has looked at objects as a mediator of collaboration and communication in organisational settings. Designers in particular are effective in generating and utilising objects which are visual. Designers, by their nature, education and training have expertise in the generation of ‘epistemic’ objects; visualisation through modelling, prototyping, sketching and drawing is a core skill. Previous studies have mainly focused on innovation or new product development in an organisational setting. In such a setting, the expected outcomes are unambiguous, and the actors involved know their role in progressing from idea to market. In the science base however, and especially for researchers operating at an early stage, there is not such a clear objective and thus, the rationale for including designers is not so clear.

We might therefore expect that the demonstrators produced at an early stage of research in the laboratory are different to those which seek to explore commercial opportunities. However, this subtle distinction is rarely recognised in literature. The role of physical models, prototypes and demonstrators in progressing science from laboratory to market is not fully understood. Specifically, there is little empirical evidence regarding how different types of demonstrator might be beneficial to scientific activity in its broadest sense.

2.1. *Progressing scientific theory from laboratory to commercialisation*

To provide a lens by which this phenomenon might be explored, it is first necessary to understand the scope of scientific research, and especially the way in which research might progress from laboratory to market.

Eder et al. (1993), define science as “having knowledge; a branch of study concerned with observation and classification of facts and especially with the establishment of verifiable general laws; accumulated systematic knowledge, especially when it relates to the physical world.” This rather purist vision of scientific exploration prioritises knowledge generation and pays little attention to the application of that knowledge. Most often, this quest for knowledge is described as following the ‘scientific method’ (Niiniluoto, 1993). According to Bauer (1992) p.19 the scientific method is conventionally defined as the “systematic, controlled observation or experiment whose results lead to hypotheses, which are found valid or invalid through further work, leading to theories that are reliable because they were arrived at with initial open-mindedness and continual critical scepticism”.

Thus, the process of scientific research might be viewed in a linear fashion, progressing through stages of experimentation/ observation, hypothesis, testing and generation of theory. Stokes (1997) p. 6 cites Harvey Brooks, emphasising this linear character of research: “any research process can be thought of as a sequential, branched decision-making process. At each successive branch there are many different alternatives for the next step”. This linear model is often extended to encompass both the generation of knowledge and also its application, with a distinction between scientific activity which is either ‘basic’ or ‘Applied’. According to Pielke and Berly (1998) and Stokes (1997) this classification has its origins in the “linear/reservoir” model drawn in Vannevar Bush’s 1945 report “Science-The Endless Frontier”. In this model, Bush argues that basic research outcomes create a “reservoir” of knowledge that underpins applied research. This applied research is “appraised by criteria external to science” and leads to development. Thus, “basic” research is often viewed as a precursor to “applied” science.

Perhaps the mostly widely accepted embodiment of this linear view is the classification of scientific research produced by the Organisation for Economic Co-operation and Development (OECD). This classification focuses on the different purposes of scientific research, with three distinct categories (OECD, 2002); Basic Research, Applied research and Experimental development:

- **Basic research:** experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view. As a variant of basic research, the OECD identifies *oriented* basic research which is carried out with the expectation of generating a “broad base of knowledge likely to form the basis of the solution to recognised or expected, current or future problems or possibilities” p. 78.
- **Applied research:** is aimed towards a “specific practical objective”. In this type of research, researchers address their efforts towards identifying potential applications, or finding novel ways of achieving “predetermined objectives”. Here, the researchers’ main driver shifts from understanding the world towards finding ways to transforming it.
- **Experimental development:** is explained as “systematic work” that uses “knowledge gained from research and practical experience, that is directed to producing new materials, products and devices; to installing new processes, systems and services; or to improving substantially those already produced or installed” OECD (2002) p. 79. Experimental development sits in the boundaries of scientific research, and may often be part of different contexts such as industrial or commercial activity.

Although the categorisation of scientific research into basic and applied is commonly accepted in the scientific community, Webster (1991) argues that distinctions between pure and applied sciences are becoming irrelevant in the current context of interdisciplinary research, where scientists with interest in basic and applied science collaborate. Webster suggests that even the boundaries between scientists working in academia and technologists working in industry are blurred, since scientists (pure or applied) are more often “found within industry than anywhere else” p. 3.

From a different point of view, Stokes (1997) developed a ‘Pasteur’s quadrant’ to explain the relationship between ‘basic’ scientific research and technology development or ‘applied’ research. In this model, he proposes a third category of research motivated by the pursuit of understanding fundamental principles and also their application, which he called ‘use-inspired basic research’. Similarity can be seen with a classification of scientific research by Niiniluoto (1993), which introduces the concept of



Fig. 1. Integration of science and technology readiness levels.

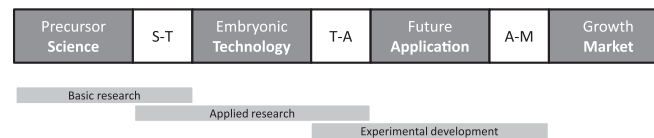


Fig. 2. STAM model, adapted from Phaal et al. (2011) and the OECD model.

technology as an integral part of scientific research. Niiniluoto argues that basic research seeks to generate knowledge, whilst technology is focused with the creation of material and social artefacts. Between the two, applied science seeks to develop knowledge and to develop useful material and social artefacts. Indeed, some authors describe a complex and iterative relationship between technology and scientific research; science feeds technology and technology feeds science in an iterative process (Nelson and Rosenberg, 1993, p. 7).

This role of technology in enabling the progress from basic to applied research is recognised in the Technology Readiness Level (TRL) framework, developed by NASA to assess the ‘maturity’ of technologies (Mankins, 1995). The framework classifies technological development in nine stages ranging from TRL 1 ‘basic principles observed’ to TRL 9 ‘actual system proven’, and includes the 7 intermediate stages (Fig. 1). Between TRLs 4 and 7, the way in which progress is described is in terms of the physical artefacts as embodiments of the technology at each stage, indicating that prototypes or demonstrators of one type or another are critical for progression from science to marketable technology.

The TRL framework is applicable once the ‘basic principles’ or scientific underpinnings have been observed. In other words, it is relevant towards the ‘applied’ end of scientific enquiry. To help manage more fundamental scientific research, Millis (2005) describe Applied Science Readiness Levels (ASRLs), which consists of 3 stages from describing the ‘general physics’ through to the observation of the desired effect. Within each stage, there are 5 steps which represent the scientific method², from ‘recognising the problem’ through to reporting of results. According to Millis, this equates to 15 levels of relative maturity, with the most

advanced level being equivalent to technology readiness level 1. Thus, Millis views both the ASRL and TRL models as connected. Combining both models, it is possible to generate a detailed picture describing the stages of scientific and technological enquiry (Driver et al., 2011). Here, the ASRL is drawn to show three iterative phases of activity. The TRL scale follows this and progresses in a linear path.

Phaal et al. (2011) provide an extension of this basic model, to suggest how a technology might progress towards the market place. This framework aims to show how scientific enquiry makes the journey from laboratory to commercial products (Fig. 2). Conceptually, it represents the same journey described by the OECD definitions.

In their model, Phaal et al. outline a ‘precursor’ phase that represents “the scientific developments that act as the initial conditions for technology-based industrial emergence and an ‘embryonic’ phase associated with the translation of applied science proof-of-concept demonstrators into technology prototypes and early application demonstrators.” This precursor phase might be considered as the ASRL scale, whilst the progression towards application is equivalent to the TRL scale. Fig. 3 shows all of these models concurrently to highlight their overlaps.

Although many practitioners would describe the journey of research from lab to market as being iterative and unpredictable, it is often visualised using linear process models, for both simplicity and pragmatism. These broadly linear models have the advantage of presenting a path from a starting point to an end point, with plausible phases or activities in between. However, their linearity masks inherent complexity. Within this complexity, it is physical artefacts that provide critical ‘way-points’.

Both the STAM and the TRL models provide indicative descriptions of the types of artefacts which might be produced on through the process. However, these tend to focus on resolution of technical issues. Phaal et al. produced a first proposal for the different types of demonstrator that might be produced as technology moves towards the market. Seven different types of

² Bauer (1992) describes the conventional definition of the scientific method as “systematic controlled observation or experiment, whose results lead to hypothesis, which are found valid or invalid through further work, leading to theories that are reliable because they were arrived at with open mindedness and continual critical scepticism”

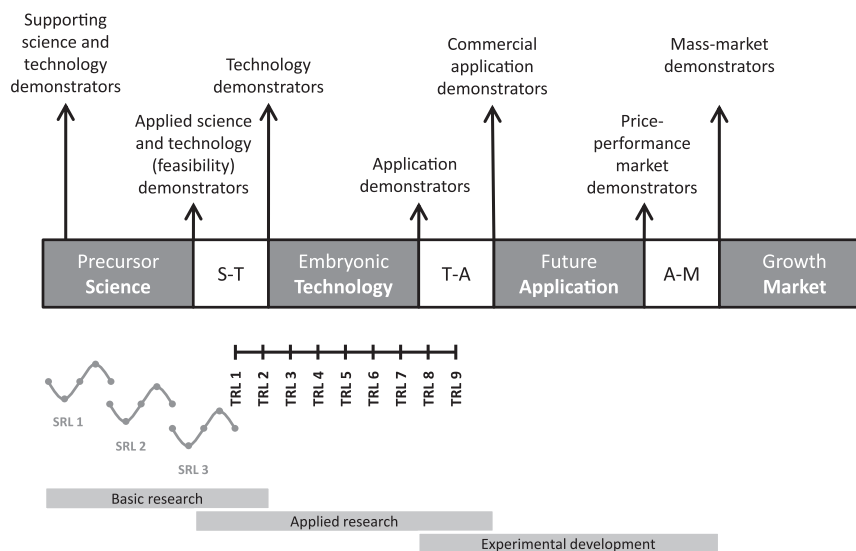


Fig. 3. OECD, STAM, TRL and ASRL compared.

demonstrator are described, each aligned with the STAM sequence; supporting science and technology demonstrators; applied science and technology (feasibility) demonstrators; technology demonstrators; application demonstrators; commercial application demonstrators; price-performance market demonstrators; and mass market demonstrators. However, they present these categories as a conceptual proposal and do not provide any explicit evidence of either the origin or validity of these categories.

Recognising the inherent limitations of linear models, this paper takes the STAM model as a basis for mapping the different artefacts produced in two collaborative projects between designers and scientists. Throughout these collaborations, the different types of physical artefact (model, test rig, documents, prototypes, demonstrators) created by both designers and scientists were recorded in order that they might be analysed to better understand their purpose and what role they play in progressing the scientific activity from idea to market. The adoption of the STAM model was felt to have several advantages over the alternatives:

- There is a pre-existing proposed classification of demonstrators already aligned with this model. Thus, a direct comparison might be made.
- Unlike both the TRL and ASRL models, STAM is broad in scope, spanning the whole space from early stage scientific discovery through to application and commercialisation.
- It was felt to be sufficiently conceptually clear that it could be used in conversation with scientists with little ambiguity or controversy.

The next section describes the research approach adopted and the two case studies.

3. Research approach

The research was conducted by a team of two designers and a senior academic acting in a reflective role. This team will hereafter be referred to as the design team. The design team undertook a series of 8 case study design projects with scientists from the University of Cambridge. Case study partners were selected to represent a variety of disciplines and stages of scientific development. Individual case study collaborations lasted around 6–18

months, and during the projects, data was recorded using a combination of notes, sketches, visualisations, photographs, models, voice recordings and videos. In each case, a detailed record of the main design tasks was noted.

In this paper, results from two of these case study projects are reported: Bio-photovoltaics (BPV) and Fluid handling device (FHD). These were selected as they represent projects at both ends of the science-application spectrum. The BPV project was aiming to understand the fundamental physics behind the generation of electricity through photosynthesis of organic matter. The FHD project was seeking to explore the commercial potential of a new technique for handling fluids in immuno-assay experiments. These two case studies will both be briefly described below, before describing in more detail the approach to collecting and analysing data regarding demonstrators.

3.1. Case study 1: Bio-photovoltaics (BPV)

A team of scientists from the Chemical Engineering and Biotechnology, Plant Science and Biochemistry departments were collaborating on the development of Bio-photovoltaic (BPV) technology. BPV devices generate energy from the photosynthesis of living organisms such as algae or moss. They had produced a small device in the laboratory and were focussing their research efforts on characterising the system in order to obtain repeatable results so that they could publish papers. The scientists estimated that a commercially viable device was 10–20 years away.

The design team arranged an initial meeting with the scientists by offering to help with the design of an exhibition stand for a science festival. The designers suggested that the scientists participate in a brainstorming session to generate future product concepts, which they then visualised for inclusion in a poster for the exhibition stand. These concepts included an algae solar panel, a floating 'lily pad' power station and a table incorporating a BPV device. The design team suggested that they manufacture the algae solar panel so that the scientists could demonstrate to potential funders how the technology might be embodied. To achieve this, they worked with a member of the scientific team who was then able to test the device. Following the success of this collaboration, the designers proposed that they manufacture the BPV table and exhibit it at design shows (e.g. London Design Festival, Milan Furniture Fair) to raise public awareness of the technology. The scientists agreed, and a successful funding application was

Table 1
Design tasks in the BPV case study

Design task	Participants (D=designers, S=Scientists)	Duration
Initial meeting	D, S	½ day
Briefing meeting	D, S	½ day
Draft project proposal and visualisation	D	2 days
Brainstorm	D, S	½ day
Laboratory visit	D, S	1 day
Concept design for poster	D	10 days
Prototyping algae device	D	10 days
Testing 1	S	1 day
Amendments algae device	D	6 days
Testing 2	S	1 day
Write moss table funding application	D, S	2 days
Write magazine article	D, S	1 day
Write research proposal	D, S	3 days
Prototype moss device	D	10 days
Testing	S	1 day
Prototype moss array	D	4 days
Design moss table	D	5 days
Total		58.5 days (over 18 months)

made to produce the table.

As a consequence of these activities, the scientist asked the design team if they would be willing to contribute to a joint research proposal with an overseas university to develop a floating device. The proposal was co-written by the designers and the scientist. The designers and scientists also co-wrote an article about the technology for a science magazine following an enquiry made at the science festival. As summary each of the key design tasks is provided in [Table 1](#). Activities which are conducted by individual participants are the result of discussion and agreement during collaborative meetings.

3.2. Case study 2: fluid handling device (FHD)

Two biological chemists had an idea for a fluid handling device that could significantly reduce the time taken to perform a very common laboratory test called an immuno assay. They had created a Micro-Capillary Film (MCF) which enabled a ten-fold reduction

in experimental time. This MCF had been demonstrated in the laboratory, but the scientists did not know how to translate this into a device with commercial potential. They approached the university Technology Transfer Office (TTO), who in turn suggested that the design team might assist in the creation of a working prototype.

The designers initially struggled to understand the key strengths of the scientists' concept, as the process being described was complex and the scientists were using highly technical terms. The design team asked if they could observe a typical immuno assay procedure and a simulation of the new system that was being proposed.

The designers spent a day in the lab with one of the scientists, recording the standard procedure and the procedure enabled by the MCF, using notes, sketches, pictures and video. They noted issues related to the use of the device such as sealing, interfacing with standard lab equipment and the risk of human error or contamination. The scientist gave an explanation of the chemical processes occurring within the device using symbols drawn in his lab book.

Following the observation day, the designers created a visualisation of the processes followed and used this document to confirm with the scientists they had understood the key benefits and operating principles of the device. The design team then created a design brief that included some of the key issues that arose during the observation day; including modularity, labelling and human error caused by fatigue, and boredom or stress. Once this had been approved by the scientists, the designers generated a series of design concepts. As the device was dealing with liquids, adequate sealing was identified as a critical issue and thus the designers accompanied concept ideas with sketch-models, which enabled them to evaluate the technical feasibility of each idea. The designers also produced drawings to visualise how the device would be used as part of an experimental kit. This expanded on the scientists' original ideas to turn the basic concept into a viable system.

The sketch models helped the scientists to define a key principle of the device's operation which would ensure that air bubbles were not introduced. These artefacts also helped to build rapport between the scientists and the designers at the first progress meeting.

Based on insights from observing the process, the designers conceived a sample-tray which had the potential to make the process even quicker than originally anticipated, as well as

Table 2
Design tasks in the FHD case study.

Design task	Participants (D=designers, S=Scientists)	Duration
Speculative meeting	D, S, TTO	½ day
Draft project proposal	D	1 day
Briefing meeting/ Lab observation	D, S	1 day
Draft design brief	D	1 day
Concept design and sketch modelling	D	9 days
Feedback meeting 1	D, S	½ day
Prototyping	D	5 days
Feedback meeting 2	D, S	½ day
Testing	S	2 days
Feedback meeting 3	D, S, TTO	½ day
Project report	D	3 days
Handover to external consultants	D, S	1 day
Total		25 days (over 9 months)

reducing the likelihood of errors. The scientists especially liked this concept and thereafter the tray became a core component in the device's specification.

The designers produced a prototype device using rapid prototyping facilities. Sealing to prevent fluid leakage remained a challenge, but through a process of iteration a configuration was produced that enabled the scientists to perform their experiments. The scientists were now able to use the prototype to gather data and compare their concept with existing technologies. This, in combination with sketches, visualisations, models and prototypes produced by the designers, formed the basis of a funding application for ongoing development.

Unbeknownst to the scientists, the designers also prototyped a device with integral capillaries to challenge the scientists' use of the material developed within their lab. At the next feedback meeting, this prototype stimulated significant debate as to the unique properties of the material and the intellectual property claimed. As a result, the scientists produced a document specifically to refute this as a viable alternative.

The scientists were subsequently awarded £150,000 of which they allotted £25,000 for the provision of external design support to develop and manufacture small batches of the devices for lab trials.

As summary each of the key design tasks is provided in Table 2. Activities which are conducted by individual participants are the result of discussion and agreement during collaborative meetings.

3.3. Approach to analysing the artefacts produced

During the case study projects, detailed records were kept of each design meeting and any artefacts produced by the design team, the scientists or both. It was anticipated that we would be able to simply map these against the STAM model in order to develop a classification of types of technology demonstrator. However, once the case studies were complete, this task proved to be not so simple. It was evident from discussions with the scientists that in progressing scientific work, there is often simultaneous consideration for science, technology and application to varying degrees. Despite the models describing a linear process, real research does not necessarily follow an archetypal 'linear path' from understanding fundamental principles to application development, but rather shifted in focus continuously over the course of the project.

As a result, in order to map the artefacts produced against the STAM model, we created a chronological list of each of the 'artefacts' created during the case studies, including sketches, models, prototypes and visualisations. For each artefact, we asked the scientist to score the extent to which enabled progress at each stage of the STAM model. Specifically, they were asked to apportion 10 marks across the STAM framework. So, if the artefact was completely directed towards scientific discovery, then it scored 10 points under 'Science'. However, if it enabled both the

understanding of the fundamental principles and also embodied potential technology, then it might score 5 in each category. Scientists were also asked to comment on the benefits and role of each individual artefact.

At this point, it became apparent that in order to score these in a reliable way, the definitions used to explain each stage of the STAM model were extremely important. As described currently in literature, there is room for ambiguity and thus inconsistency in scoring. We needed phrasing that would be unambiguous, but also clearly understandable by the scientists.

It is clear that generating new knowledge of fundamental principles can be classified as a contribution to 'science', (S) and that embodying technology in a commercially exploitable form demonstrates a focus on the 'market' (M). What is less clear however is how to differentiate between contributions to the development of 'technology' (T) and 'applications' (A). Agassi (1980) states that "the chief difference between scientific and technological research is a matter of objectives: scientific research aims at increased understanding and technological research at increased usefulness". Interpreting 'usefulness' as 'being useful for a broad range of applications', one could differentiate between technological research (T) and application development (A) by stating that the latter is focused on the development of technology for a *specific* application. The former (T) is appropriate for *multiple possible* applications.

To bring this to life, we used a concrete example to illustrate the definitions; the development of radio. James Clerk Maxwell's explanation of the relationship between electricity and magnetism in 1873 was a key scientific discovery (S). The demonstration of wireless transmission by Nikola Tesla in 1893 could be described as a technological breakthrough as it had broad application (T). The development of the first radio transmission system by Marconi in 1896 demonstrated the development of wireless technology specifically for a communication application (A). Finally, the first commercially available radios indicate readiness for the market (M).

Combining these notions, scientists were presented the following definitions for each stage in the STAM model:

- **Science:** To what extent did the creation of this artefact generate new knowledge about fundamental principles? *For example, the relationship between electricity and magnetism explained by James Clerk Maxwell in 1873.*
- **Technology:** To what extent did the creation of this artefact demonstrate something potentially useful that would be applicable to a broad range of applications? *For example, Wireless transmission demonstrated by Nikola Tesla in 1893.*
- **Application:** To what extent did the creation of this artefact support the development of the technology for a specific application? *For example, the first radio transmission system developed by Marconi in 1895.*
- **Market:** To what extent did the creation of this artefact embody the technology in a commercially exploitable form? *For*

Table 3
Example of scientists scoring for different artefacts.

Artefact	Who made it?	Purpose	Science 0-10	Technology 0-10	Application 0-10	Market 0-10
BPV1	Scientists	Prove the concept of a photo-microbial fuel cell. Proved the concept. Inconsistent results. Made successful grant application.	7	3	0	0
Algae solar panel 2	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the Royal Society exhibition. Resolved practical sealing issues.	0	7	2	1

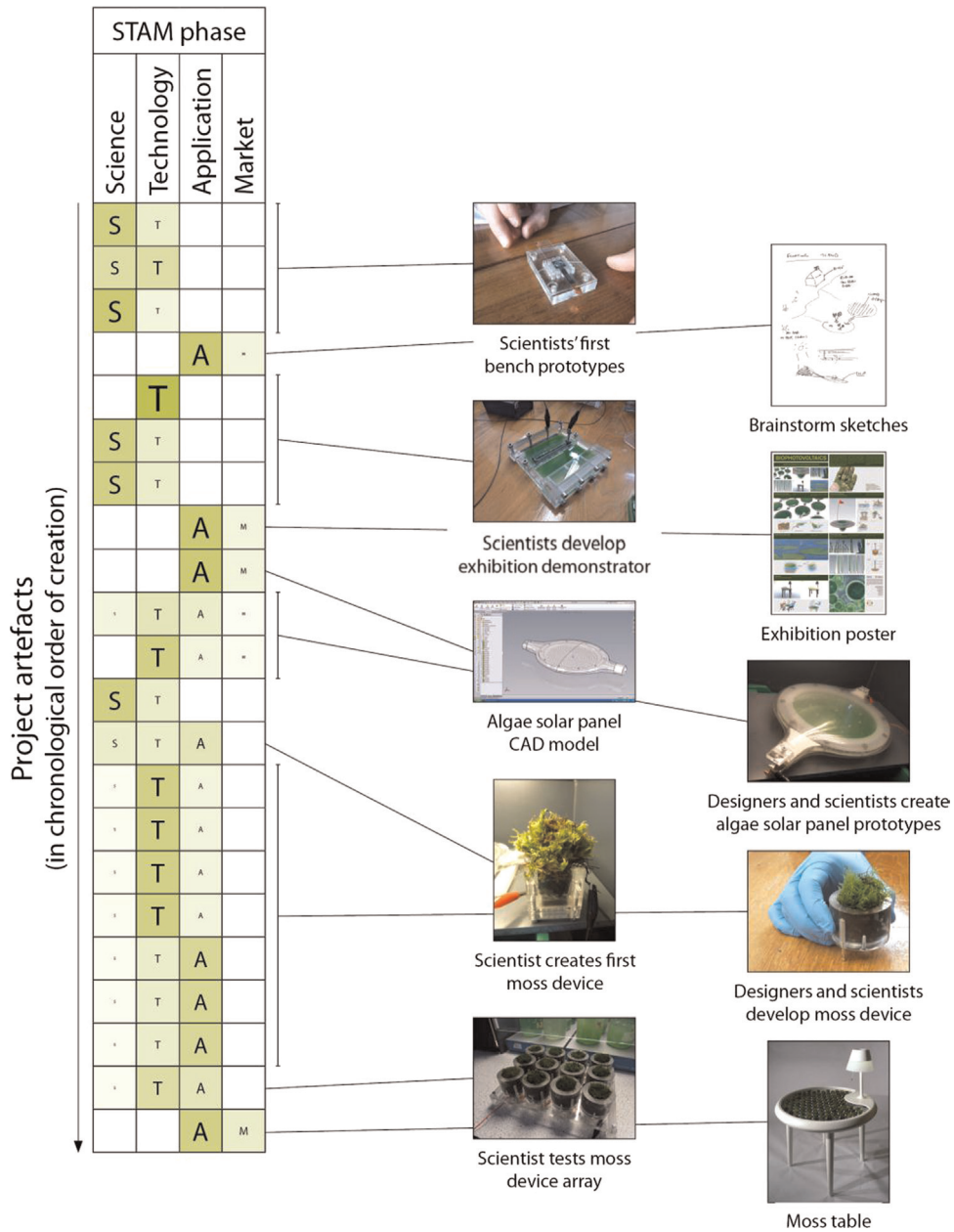


Fig. 4. STAM analysis of Bio-photovoltaic case study.

example, the development of first commercially available radio.

An example of the scoring performed by scientists is provided in Table 3. Here, 'BPV1' was a bench prototype created by the scientists before the design team became involved in the project. BPV 1 demonstrated the basic working principles of BPV and thus the scientist gave a very high score for 'Science' as it generated significant new knowledge of fundamental principles. He also gave it a small score for 'Technology' because it had proved that the technology worked (or could be put to use in a broad range of applications). By contrast 'Algae solar panel 2' was created by the designers and the scientist halfway through the collaboration for the purpose of demonstrating a potential future application of BPV technology. Here the scientist provided a high score for 'Technology', because in addition to developing a specific application, this prototype provided significant insight into issues of scale-up which could have broader application. A token score of 1 was also

given to 'Market' because the prototype embodied the technology in a form which the designers hoped might have commercial appeal.

Detailed results from this scoring are provided in Appendix A and Appendix B. To aid interpretation, these results are summarised graphically in Figs. 4 and 5. Here, the scores provided by the scientists were used to scale the font corresponding to the STAM initials. So, where 'T' is dominant, it has a much larger font. If the prototype serves to contribute to all STAM elements equally, then the letters have a smaller, consistently sized font. In addition, a tone has been applied to further emphasise the scoring and enable the progression to be more clearly seen at a glance. In Figs. 4 and 5, images of some of the artefacts and prototypes have been used to illustrate key milestones in the project as well as periods of development.

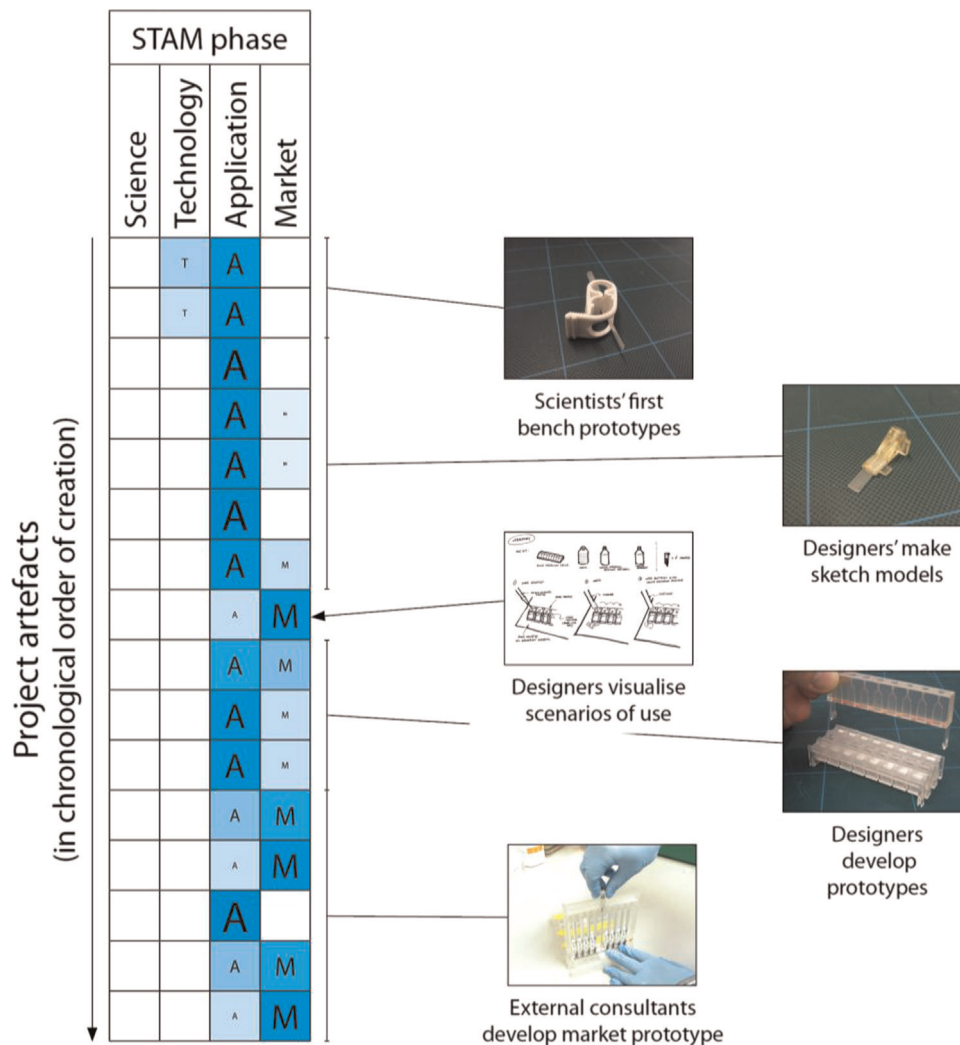


Fig. 5. STAM analysis of fluid handling device case study.

4. Analysis of artefacts

4.1. BPV

The starting point for this collaboration was work which was in an early stage of scientific exploration, where the scientists were addressing fundamental principles. The STAM analysis (Fig. 4) broadly demonstrates a shift in focus from basic science, to technological development and finally application development. However the transition is not linear, where each element (STAM) is tackled in isolation before progressing to the next. There were several occasions in which the desire to achieve a proposed application was a driver of scientific and technological activities. For example, the creation of the algae solar panel prototype provided the scientists with insights into scaling up the technology, and also enabled them to gather scientific data to verify the formation of desalinated water. Similarly the decision to build the table application led the scientists to explore the use of moss rather than algae. This resulted in the creation of a new type of device which enabled the scientists to make significant contributions to knowledge.

Thus, the results also clearly indicate the mix of contributions made by individual artefacts. The first solar panel prototype for example made a contribution to each phase of the STAM

framework; it represented a potential commercial embodiment of the technology, an application demonstrator, a test rig for scaling up the technology and a piece of experimental equipment for gathering data on the production of desalinated water.

With the exception of the brainstorming sketches, the first artefacts were created by the scientists independently of the design team. It is interesting to note that the same non-linear and multi-focus behaviours were exhibited by the scientists in the course of their normal research. For example the scientist's first prototype resulted in a significant scientific discovery which in turn enabled development of technology. As the devices improved in performance, the scientists could use them to gather reliable scientific data to support new theories. What's more, each new artefact shed light on fundamental principles whilst simultaneously representing a step towards a functioning device. These observations give an indication as to the nature of 'normal research' and support the assertion that scientific research is highly iterative.

The exhibition poster created after the brainstorm was a key artefact in the collaboration as it provided a vision of market-ready embodiments of the technology in a variety of applications. This provided the basis for future application development which in turn fed back into the research.

4.2. Fluid handling device

This collaboration was instigated due to the desire of the scientists to commercialise a technological breakthrough. The STAM analysis (Fig. 5) demonstrates that the collaboration was strongly focussed on the development of a specific application and the embodiment of the technology in a commercially exploitable form. This is what we expected. However, the results do reveal some interesting behaviour. For example the visualisation of ‘scenarios of use’ of the device proved to be a key artefact of the collaboration. This visualisation provided an original vision of how the device might be used by consumers as part of an experimental kit and drove subsequent application development. For the scientists, this ‘designerly’ approach to markets and users was a surprise, and marked a change in their mind-set from ‘technology-push’ towards beginning to understand what users might value and how this technology might be used in practice. Recognising the challenge of the ‘valley of death’, this is one area in which designers have the potential to make a significant difference; designers are inherently attuned to being the user’s champion and are able to translate the technological features into user benefits. In contrast, the scientists engaged in this project expressed their technological breakthrough in terms of features, numbers and specifications.

The external design consultants went through a similar process

when they took over the project, creating foam models to visualise how the finished device might look and be used. We can also see that the collaboration did not result in a contribution to basic science or technology with wider application. Thus, through examining the artefacts, we can see that the demonstrators enabled progression towards commercialisation, but not to understanding basic scientific principles.

5. A new classification of design demonstrators

From these results, we can observe that the STAM analysis of project artefacts provides an effective means of visualising the non-linear nature of scientific research. We expected to see a close mapping between the different artefacts produced and the relative maturity of the technology. In reality, this mapping is much more subtle and varied than we anticipated.

Scientific research can be highly complex in nature and may simultaneously pursue both basic and applied goals. As a result, it is highly difficult to precisely categorise the different types of demonstrators according to stages of the STAM process. The process itself is iterative and multiple goals might be achieved through a single demonstrator. Thus, the role of demonstrators is much more subtle than that indicated in Fig. 3 as proposed by

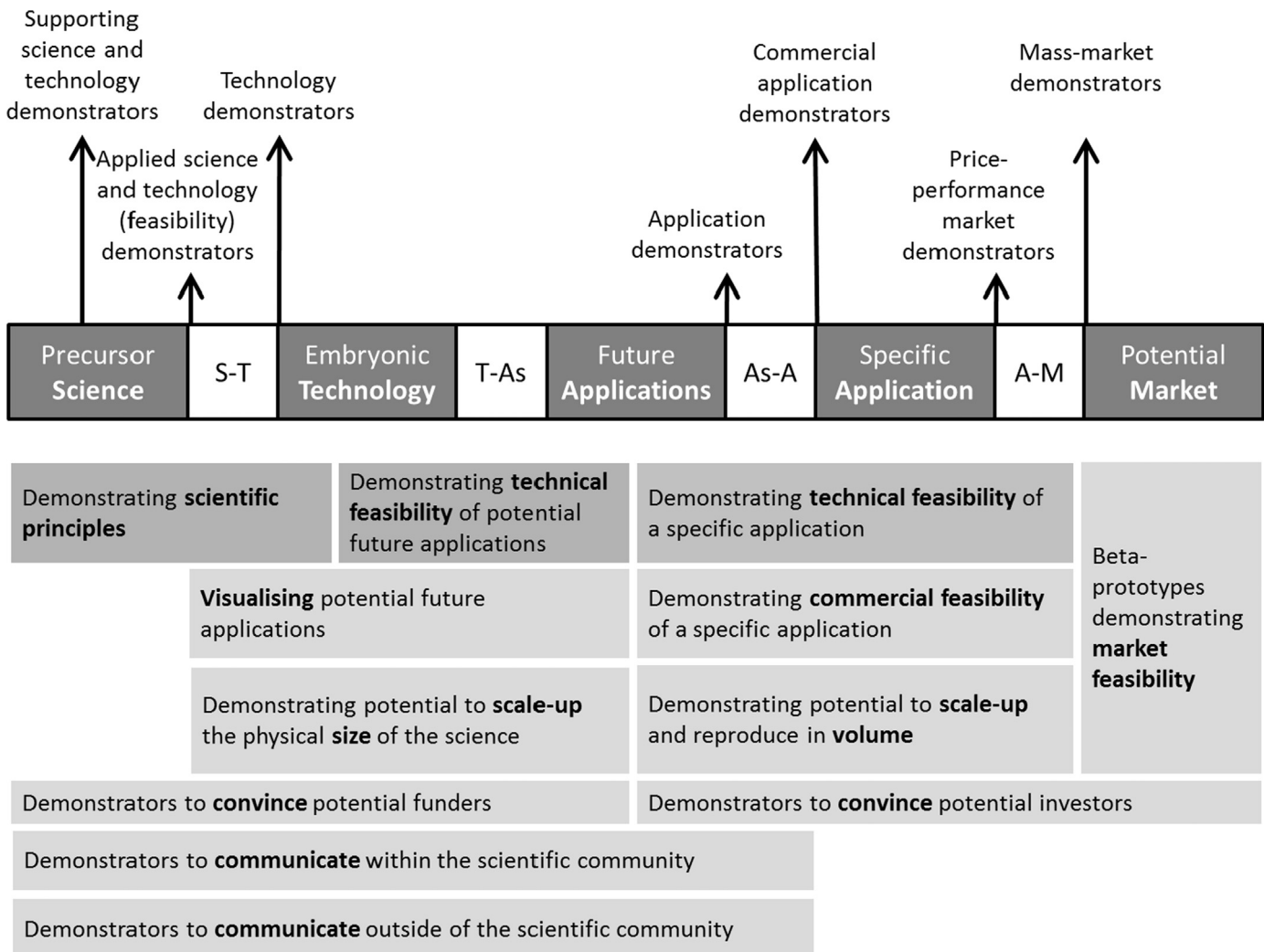


Fig. 6. : Model of different types of design demonstrator.

Phaal et al. (2011). As a result, we propose a modification to this model that aims to better capture the role of the various types of demonstrator (Fig. 6).

In this revised model, there is one important change. In our case studies, it was evident that a distinction can be made between the consideration of multiple future applications of an embryonic technology (or precursor science) and the development of one of these as a specific application. In the BPV case study for example, demonstrators were produced to embody different potential applications and each asked different questions regarding the ability of the underlying science to enable these applications.

In both case studies, we observed that it is not possible to assign a demonstrator to a specific point of the journey from science to market. Demonstrators tend to play a more complex role. Instead, we have tried to capture a set of 'reasons' for which a demonstrator might be produced across the different stages.. These include:

- **Demonstrating scientific principles:** this could be a standard 'bench prototype' (e.g. BPV 1), with a primary goal of supporting the scientist test or demonstrate the underlying scientific principles in their domain.
- **Visualising potential future applications:** this may not be a standard consideration for many scientists, but visualisations of possible future applications proved to be critical artefacts in our case studies. These visualisations stimulated discussion regarding the enabling science and the likely market potential. Ideas generated in brainstorming sessions between the design team and the scientists were later visualised by the designers. This served to encourage the identification of a sequence of research questions which would have to be addressed by successive demonstrators in order to achieve the end application.
- **Demonstrating technical feasibility of potential future applications:** These demonstrators are driven by a desire to demonstrate the technical or scientific embodiments which might enable alternative possible applications. At this stage, these technologies might not be application specific. These demonstrators are likely to be at a laboratory scale.
- **Demonstrating technical feasibility of specific applications:** prototypes or test rigs that are created with a specific application in mind in order to demonstrate the technical viability of this application.
- **Demonstrating commercial feasibility of a specific application:** these prototypes might not 'function' in a technological sense, but can be used to establish the possible commercial feasibility of a specific application. This was seen in the FHD project, with 'looks like' models to help communicate the mode of use of the device.
- **Demonstrating potential to scale-up physical size of science:** many demonstrators are at 'lab bench' scale. In our case studies, simply increasing the physical scale of these prototypes is an important precursor to progressing towards possible applications. This might happen without specific applications in mind.
- **Demonstrating potential to scale-up and reproduce in volume:** Many demonstrators of scientific principles are a 'one-off', often embodying the tacit expertise of the individual scientist. As a one-off, components are custom made to fit and might mask the challenges of working to production tolerances. Again, our case studies highlighted the importance of being able to produce in greater volume as an important precursor to progressing towards possible applications. Again, this might happen without specific applications in mind.
- **Demonstrators to convince potential funders:** we observed in the BPV project that visualisations of future applications were of benefit in the formulation of applications for research funding and also helped in creating a persuasive case for

enabling research.

- **Demonstrators to convince potential investors:** an important step in commercialisation is the identification of possible investors. It is possible to conceive specific demonstrators that will help convince investors in the commercial and technical viability of the science. These demonstrators might also help capture the exiting potential of the science when conceived as a real product.
- **Beta-prototypes demonstrating market feasibility:** as the technology progresses towards the market, prototypes are likely to be reflective of the products that might be seen in the market place, but they are still seeking to provide insight regarding the usage and likely uptake of the nascent idea. For the FDH project, 'Design agency device 2' fulfilled this specific purpose.

In addition to the translation of scientific work from bench to application, there is another dimension to scientific work. Grinnell (2009) describes an important aspect of scientific research which relates to the social interaction of scientists with the scientific community. This interaction operates when scientists seeking to transform their findings into scientific knowledge "turn to other scientists to establish the credibility of the work" (p. 60). Researchers compare their ideas and results with other researchers, submit their findings for peer review in specialised journals, put their results under public scrutiny in conferences and symposiums, apply for funding to scientific funding bodies, and explain their findings and work in outreach activities.

Thus, we can see that there are two distinctive and interconnected dimensions in the practice of scientific research, the 'rational' and the 'social'. Rational activities relate directly with the subject of study and all activities of discovery. The second dimension is linked to the interaction of scientists within the science and the wider community, and all activities related to pursuing credibility. Thus, there are additional types of demonstrator that might be produced:

- **Demonstrators to support communication within the scientific community:** Within the community, demonstrators and clear visualisations help convey the core scientific messages.
- **Demonstrators to support communication outside the scientific community** Outside of this community, demonstrators serve to 'translate' the scientific language into concepts more readily understandable.

As a final observation, it is useful to note that whilst these any of these demonstrators might be produced by scientists, in a majority of cases, the involvement of professional design skills can have a transformative effect. This was certainly evident in both case studies. In the BPV project, the scientists understood the potential value of demonstrators which communicated outside of their domain, but did not have the skills with which to produce these. Similarly, in the FHD project, the scientists new they needed to demonstrate market feasibility, but again did not have the requisite knowledge or skills. To reflect this, in Fig. 6, those demonstrators which are naturally in the domain of the scientist have been shaded in a darker tone. Those which are naturally in the domain of the designer have been given a lighter tone. This highlights the potential of designer involvement even in the early stages of scientific enquiry.

5.1. Demonstrators as boundary objects

In a product development, innovation or design setting, boundary objects are typically discussed in terms of cross-disciplinary collaboration (e.g. Nicolini et al., 2012). The technology

demonstrators produced in this study show many of the characteristics of boundary objects:

- They make collaboration possible (Nicolini et al., 2012: 616).
- They help manage the tensions between divergent viewpoints (Bowker and Star, 1999: 292).
- They make tacit knowledge explicit, including visual and kinesthetic knowledge (Henderson, 1991: 451).

However, in some ways, they are quite different. Boundary objects normally emphasise the notion of a 'boundary' in the form of different knowledge, perspective, seniority or even a physical location which needs to be spanned. In so doing, the very boundary being spanned is reinforced and brought to the fore. The basic metaphor sets up the potential for problems when actors with different skills, knowledge, status or location interact. The 'boundary' is brought to the fore, and in particular, the tensions that exist across these boundaries (Subrahmanian et al., 2003). Hence the need for tangible artefacts to support collaboration, to make knowledge explicit and manage tensions across this boundary. The boundary object is thus a solution to this challenge.

However, in the case studies observed, whilst there were differences in knowledge, it was not evident that the apparent knowledge boundary was problematic. Indeed, the different skills and perspectives were an asset to mutually beneficial collaboration. The demonstrators and prototypes were as a result of this collaboration, rather than an aid to enable it. Their production relied upon utilising the skills and knowledge of both parties. As a result, they seemed to have a much more purposeful ambition towards addressing future oriented tasks.

Ewenstein and Whyte (2009) suggested that a distinction can be made between 'epistemic' and 'technical' objects. In the two case studies, we see the designers contributing to a progression from epistemic objects, which serve to 'conceptualise and enquire' towards more concrete 'technical objects'. However, we also observed a separate group of objects which did not specifically support this journey from idea to market. Instead, these objects sought to facilitate the translation of knowledge from one domain to another; and not just within the specific context of the collaboration. The designers, with their proclivity to visualise were uniquely placed to take this role as translator and intermediary between knowledge domains. The resulting artefacts might be thought of as '**translator objects**', as opposed to boundary-objects.

In this capacity, the designer and these translator objects serve to span the immediate designer-scientist boundary, but also the boundaries between scientists and their scientific community. Perhaps more importantly, these objects were also effective in enabling the scientists to span the boundary between the public and the science base to better communicate the potential purposes of the scientific enquiry. Finally, these translator objects also aid in communicating to potential investors. In the BPV project for example, the Moss Table acted as an experimental artefact to demonstrate the potential to scale up the physical size of the technology. It also acted as a translator object to help communicate this to a wider public audience, notably at London Design Week. It was also instrumental in supporting further proposals for funding. In the FHD project, visualisations of scenarios of use helped translate the technological invention into understandable user benefits, which aided in securing follow on funds for commercialisation.

In both projects, these translator objects were a key pre-cursor to more creative or conceptual ideation and 'epistemic objects'. In its turn, this conceptual work results in objects which then support further translation of ideas and knowledge between the two knowledge communities. A surprising effect of this iteration was the impact of these demonstrators on the generation of new

research questions being asked by the scientists.

Designers are perhaps uniquely placed to conceive of and produce these complex objects which enable translation, ideation and also experimentation.

6. Conclusions

This study has provided insight into the different types of design demonstrator that might help scientific research progress from the laboratory to the market place. An original model is proposed that categorises these demonstrators by referring to the purposes which they might fulfil. As a result, we propose a modification to the established 'STAM' (Science, Technology, Application, Market). In our revised model, 'Application' is split into two categories; potential applications, and specific application.

We observed that there is not a one-to-one mapping between a single type of demonstrator and an individual phase of the STAM process. Indeed, evidence from case studies indicates that an individual demonstrator might fulfil multiple purposes simultaneously, and thus address different stages of the STAM process. Notably, these demonstrators provide a key role as 'translator objects' between scientists, their academic community and more widely. This is an important but often overlooked role of demonstrators, to provide an interpretation of the scientific research and represent it in new ways that have potential to inspire investors, industrialists, academics and the general public.

The various models of technology progression introduced in the literature review (e.g. ASRL, TRL, STAM, OECD) would suggest that research and technology can be considered independently from one another. However, in reality it seems that technology benefits from, and contributes to all basic, applied, and experimental scientific research. Indeed, the way in which different types of demonstrator contributes to multiple stages of the STAM model highlights the difficulty in attempting to impose a linear process upon an activity which is inherently iterative. But, linear models are easily visualised, and are therefore convenient, and so the inherent contradiction in positioning these demonstrators against a linear model is noted.

6.1. Implications

This study has brought designers and scientists together and has analysed the artefacts produced during these collaborations. These case studies individually lasted between 6 and 18 months and as a result, the number of case studies is small. This presents obvious opportunities for further work, in increasing the evidence base to further refine this preliminary model.

Whilst this work is based on a small number of case studies, there are still some interesting implications for practice:

- **Implications for scientists and research funding bodies:** The pressure for 'impact' seems to be growing, and designers might support this agenda through their ability to produce demonstrators which fulfil a multitude of purposes. However, gaining access to such skills requires funds. This implies that such skills need to be better considered in research proposals and be defensible for impact in research funding.
- **Implications for Technology Transfer Offices (TTOs):** TTOs are typically skilled in providing advice and guidance to scientists on intellectual property protection and funding for commercialisation. There would be advantages in TTOs having greater awareness and knowledge about design in order to broker relationships between designers and scientists to support commercialisation.
- **Implications for designers:** There is a potentially large market

for the work of design service providers in the science base. This is largely un-tapped, mainly due to a lack of awareness on behalf of scientists and also the perception of professional designers being prohibitively expensive. There is potential to explore new modes of engagement, beyond the traditional 'contract', in which mutually beneficial commercial arrangements would lower up-front costs to participating scientists.

Perhaps most significantly, if scientists are better informed of the range of demonstrators that are possible, then they might plan to incorporate these at the outset of a project. If a wider array of demonstrators is actively planned into a project proposal, then there might be greater uptake and exploitation of the

underpinning research, potentially making an effective bridge over the 'valley of death'.

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Appendix A: BPV artefacts

Artefact	Who made it?	Purpose	Science 0-10	Technology 0-10	Application 0-10	Market 0-10
BPV1	Scientists	Prove the concept of a photo-microbial fuel cell. Proved the concept. Inconsistent results. Made successful grant application.	7	3	0	0
BPV2	Scientists	Obtain repeatable results for publication.	5	5	0	0
BPV3	Scientists	Obtain repeatable results for publication. Paper published.	8	2	0	0
3D visualisation and schematics of bench prototype	Designers	Help the designers confirm with the scientist that they had understood the operating principles and configuration of BPV2. Scientists inspired to include 3D exploded views of devices in future academic publications.	0	0	0	0
Brainstorm sketches	Designers and Scientists	Conceptualise potential future applications of BPV technology. Embodied the benefits of BPV in concepts which the scientists hadn't previously considered important (e.g. harvesting desalinated water)	0	0	8	2
Macro 1	Scientists	Develop a device to demonstrate the technology at the Royal Society exhibition. Didn't work well	0	0	0	0
Macro 2	Scientists	Develop a device to demonstrate the technology at the Royal Society exhibition. 6 compartments effectively connected in parallel rather than series – didn't work.	0	10	0	0
Biofilm 1	Scientists	Develop a device to demonstrate the technology at the Royal Society exhibition. Published a paper.	7	3	0	0
Biofilm 2	Scientists	Develop a device to demonstrate the technology at the Royal Society exhibition. Worked well. Made 8 devices Device was also used to gather data to publish a paper on Biofilms.	7	3	0	0
Poster	Designers	Communicate potential future applications of technology at the Royal Society exhibition. Raised public profile. Catalyst article.	0	0	8	2
Algae Solar Panel CAD model	Designers	Communicate potential future applications of technology at the Royal Society exhibition. Scientist secured us funds to make 4 devices.	0	0	8	2
Algae solar panel 1	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the Royal Society exhibition. Enabled the scientists to conduct experiments to confirm that desalinated water was produced at the cathode.	2	4	3	1
Algae solar panel 2	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the Royal Society exhibition. Resolved practical sealing issues.	0	7	2	1
Biofilm 3	Scientists	Generate data for publication on Biofilms. Scientist published a paper.	7	3	0	0
'California Roll'	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	3	3	4	0

'Lasagne Sheet'	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	1	7	2	0
'Apple Crumble'	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	1	7	2	0
Foamed Aluminium	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	1	7	2	0
'Spaghetti'	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	1	7	2	0
Device configuration visualisations	Designers	Track development of devices and understand lessons learned from previous iterations.	0	0	0	0
Volume moss pots Off the shelf	Designers and Scientist	Develop a device to demonstrate an embodiment of the technology at the London Design Festival. Moss pot embodiment selected.	1	3	6	0
Bespoke I		Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	1	3	6	0
Bespoke II		Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	1	3	6	0
"What can I Power" graphic	Designers	Illustrate the current and projected capabilities of the technology in a tangible way.	0	0	0	0
12 device array	Designers and Scientist	Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	1	5	4	0
Moss Table	Designers and Scientists	Develop a device to demonstrate an embodiment of the technology at the London Design Festival.	0	0	7	3
Exhibition Graphics	Designers	Communicate to a non scientific audience: What the table is; How it works; What the potential future applications are; What the benefits of collaboration between designers and scientists are.	0	0	0	0
Exhibition Animation	Designers	Add a dynamic element to the exhibition which demonstrated that the table was working and gave a sense that it was 'alive'. Gave an indication of where we were getting the energy from.	0	0	0	0

Appendix B: FHD artefacts

Artefact	Who made it?	Purpose	Science 0-10	Technology 0-10	Application 0-10	Market 0-10
Bench prototype	Scientists	Positive results. Approached Cambridge Enterprise to commercialise idea.	0	8	1	1
Multichannel bench prototype	Scientists	Prove interface with multiple MCF. Difficult to obtain uniform sealing with MCF.	0	6	2	2
Process Visualisation	Designers	Confirm that designers understand the process stages and their purpose. Scientists impressed with graphics. Confirmed that experimental procedure had been understood.	0	0	8	2
Sketch model 1	Designers	Test laminated plastic sheet plunger concept. Poor seal.	0	8	2	0
Sketch model 2	Designers	Test modified pipette tips. Poor seal, didn't flush all liquid out.	0	8	2	0
Sketch model 3	Designers	Test horizontal modified pipette tip. Poor seal, didn't flush all liquid out.	0	8	2	0
Sketch model 4	Designers	Test silicone multichannel interface. Test one-way fluid flow. Poor seal. One-way flow seemed to work well.	0	6	2	2
Sketch model 5	Designers	Prove cassette and sample well concept. Test interference fit of MCF. Cassette and sample wells worked well. Interference fit did not work.	0	6	2	2

Scenario of use diagram	Designers	Illustrate scenarios of device use to scientists. Scientists found it useful to visualise the whole process.	0	0	6	4
Prototype 1	Designers	Test soft silicone interface with MCF. Adequate seal. Scientists used this device to gather data for funding application.	0	4	4	2
Prototype 2	Designers	Attempt to integrate capillaries into rapid prototype. Incorrect refractive index for scanning. Potential mass production issues. Scientists produced a document to justify why they would not take this approach. Conclusion was that soft MCF interface from Prototype 1 and hard pipette tip interface from Prototype 2 should be combined.	0	6	2	2
2 nd round prototype	Designers	Test gluing of MCF into cassette. Glue was difficult to apply uniformly.	0	6	2	2
Design agency concept designs	Design agency	3 concepts based on 'proof of concept model'. One with pipette interface, second with integral syringes, third with horizontal syringes. Design of semi-automatic 8-sample MCF ELISA device.	0	0	6	4
Design agency Card Models	Design agency	Demonstrate product concept and process. Most user-friendly concept.	0	0	6	4
Design agency Test Interface	Design agency	Validate syringe seal design. Perfect sealing	0	0	10	0
Design agency Device 1	Design agency	Validate design concept. Reproducibility	0	0	10	0
Design agency Device 2	Design agency	Prototype for low volume production. Performance of 8-sample MCF ELISA using semi-automatic device	0	0	6	4

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