Collaboration between Designers and Scientists in the Context of Scientific Research

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"The designers will not push the boundaries of a technology, but will put it in a context that will open new frontiers for the researcher to study"

Gault & Kogan, [2010]

"The scientific method is a pattern of problem-solving behaviour employed in finding out the nature of what exists, whereas the design method is a pattern of behaviour employed in inventing things ... which do not yet exist. Science is analytic; design is constructive."

Gregory [1966]

"The most essential thing that any designer does is to provide, for those who will make a new artefact, a description of what that artefact should be like."

Cross [2006]

"Discovery is there for everybody to pick up, it is not an invention. This brings us back to the old distinction between Art and Science. In Science there is race, a matter of getting there first, in Art you run your own race, there are no competitors."

Crick [1988]

"Interdisciplinarity (...) at its best, it engages participants in collaborative dialog, including debate and conflict, which both transforms the understandings of individual participants and produces new knowledge, new solutions, and even new disciplines that would not be possible without such dialogue."

Derry & Shun [2005]

SYNOPSIS

This thesis presents the results of a research project that examines collaboration between product designers and scientific researchers.

For this purpose, it initially illustrates the objectives and scope of the research and examines current relevant literature on the subject, highlighting its reach and limitations. The core research question is then introduced: *How can product designers and scientists collaborate and, as a result, how might designers contribute towards scientific research activity?* This question is subsequently answered in several stages.

First, the relevant literature is reviewed in order to produce an analytical framework. It examines the disciplinary characteristics of designers and scientists, the characteristics of both design work and scientific research, and the nature of interdisciplinary collaboration. This analytical framework is then used as the basis for a collaboration matrix to record and examine the collaboration between designers and scientists. Secondly, the analytical framework is also employed to help explore findings from five case studies (three exploratory and two development cases) in which designers worked alongside scientists. Finally, results from the case studies are compared with current theoretical work on the subject, highlighting differences and commonalities.

As a result of this analysis, the thesis answers the research question posed and presents as a main contribution:

-The main ways in which designers collaborate with scientists.

-The roles that designers might have while collaborating with scientists.

-The contribution that designers can offer to scientific research.

-The barriers to and enablers of collaboration between designers and scientists.

-The areas of scientific research in which design intervention can make an impact.

DECLARATION

This thesis is the result of my own work and includes nothing which is the outcome of collaborative work unless explicitly stated otherwise. The thesis has not been submitted in whole or in part for consideration for any other degree or qualification at this university or any other institute of learning.

This thesis contains fewer than 150 figures and fewer than 65,000 words.

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PUBLICATIONS

Work underpinning this thesis has been published in:

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CONTENTS

1. INTRODUCTION

Science and technology are important elements for human development and well-being. In 2007, Lord Sainsbury conducted a review of science and innovation in the UK and concluded that design might provide a means of accelerating scientific innovation, highlighting that *"evidence suggests that 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"* (Sainsbury [2007] p. 151). Additionally, there is substantial evidence that shows the value of design in the development of new technology in industry (Driver et al. [2012]), demonstrating that product design intervention can link scientific research output to industry.

There is some evidence that actual collaboration between scientists and product designers is occurring, especially in the fields of medical and testing equipment and in the commercial applications of biomimicry[1]. However, there is little scholarly research into the nature of this collaboration in the context of scientific research or into its prerequisites for success and the potential impact that designers might make in collaborative effort with scientists in scientific research.

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[1] A few good examples of collaboration between designers and scientists in academic and commercial research environments can be found on the web:

- -Simbiotica (University of Western Australia http://www.symbiotica.uwa.edu.au/welcome),
- -Material Belief (Goldsmith University http://www.materialbeliefs.com/),
- -Biomimicry Guild (http://www.biomimicryguild.com/),

1.1 Research objective

This research intends to fill a gap in empirical evidence on the subject of collaboration between product designers and scientists in the early stages of scientific research. In particular, it intends to identify the role that product designers potentially have in scientific research while collaborating with scientists, and to outline the barriers to and enablers of such collaboration.

The research also seeks to identify the nature of the contribution that product designers can offer to scientific research, and to identify those areas or activities of scientific research in which product designers can intervene. Ultimately, the research intends to offer an answer to the question *"How can product designers and scientists collaborate and, as a result, how might designers contribute towards scientific research activity?"*

1.2 Research justification and scope

It is anticipated that this research will provide an insight into the nature of collaborative effort between designers and scientists, and will offer insights into the role that designers can play in scientific research and in its link to technological development. Hence, it is expected that this research will primarily add to knowledge relating to the nature and practice of product design. However, it is expected that the research will also contribute to the field of interdisciplinary studies.

As Shanken [2005] declared when commenting on the expenditure of public money in fostering collaboration between designers and scientists, it makes sense to have "*scholarship that analyses case studies, identifies best practices and working methods, and proposes models for evaluation of both the hybrid products resulting from these endeavours and the contributions of the individuals engaged in them.*" (p. 415)

Even though all design disciplines potentially play an important role in collaboration with science, this study refers only to the sub-discipline of product design[2]. Amongst other resources, scientists generally work with "*material resources*" such as technologies and laboratory equipment, with "*practices*" such as methods and procedures, and with "*narratives, storytelling and writing practices*" to communicate their findings and activities (Styhre [2008] p. 65). From this, it seems appropriate for product designers to collaborate with scientists in the context of scientific research since they have the potential to intervene in the development and ideation of objects, in the improvement of processes and systems and in the communication of idea and concepts[3].

In the same way, and in order to limit its scope, this study refers only to scientists coming from the natural sciences (physics, chemistry, etc) and from the applied sciences (medicine and engineering).

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[2] From now on the word "designers" is used to signify "product designers". However, quotes from other authors using the word "designers" do not necessarily refer to "product designers".

[3] The ICSID (International Council of Industrial Design Societies) states that product design includes the development of *"objects, processes, services and their systems in whole life cycles."*

A review of extant literature on design and science majorly underpins the development of the argument, by presenting theoretical aspects about collaboration between designers and scientists, and the nature of design work and scientific research.

Additionally, this research also draws upon literature on Interdisciplinary Studies. Although current literature on interdisciplinarity does not directly explore the interaction between designers and scientists, it constructs theoretical principles on collaboration that can be applied to any interdisciplinary collaboration, including that between designers and scientists.

This research is part of the wider project "Design in Science" led by Dr. James Moultrie at the Institute for Manufacturing at the University of Cambridge. This project searches for answers to the question *"How and to what extent can the involvement of professional product design expertise early in scientific research improve the potential for its future application?"* (Driver et al. [2012]). It is anticipated that the conclusions of this thesis will provide insights for current and further developments of that project and for scholarly research in the areas of design, science and interdisciplinarity.

1.3 Thesis structure

Following this introduction, the second chapter, “Designers and scientist collaborating”, explains how the existing literature on collaboration between designers and scientists identifies potential ways in which designers might contribute to scientific research, as well as barriers to and enablers of collaboration. However, it also makes clear that literature on the subject is scarce and is mostly based on anecdotal evidence, and thus it reveals the need for further empirical research.

To begin to fill this gap, the chapter explores research on collaboration between designers and professionals of disciplines other than science. It shows that differences in assumptions between designers and other disciplines can affect their success as collaborators, and opens the question as to how the fundamental assumptions and values of designers and scientists might affect their collaborative effort. Finally, this second chapter takes a slightly wider view and also examines the literature on collaboration between artists and scientists. It illustrates how individual motivation, amongst other factors, plays an important role in the way that artists and scientists collaborate, and also how collaboration between artists and scientists is normally centred on artistic outputs, not on scientific outputs. The chapter concludes by setting the main research question and its sub-questions.

If Chapter 2 identifies a gap in knowledge and outlines the research questions, the third chapter, “Research Approach and Methodology”, explores the nature of the research questions, and explains the research approach. The chapter explains that the research questions are about human constructs underpinned by the behaviour of individuals (designer and scientists) interacting in a social setting (collaborative work), and thus, they are best explored through the use of qualitative research methods. The chapter describes how this was achieved through participant observation over five case studies. Throughout these cases, the researcher was both observer and designer, thus enabling the researcher to have an insider view of the phenomena being studied. The chapter also offers details as to how data was collected and presents a chronological outline of the research. It explains how the research was set up to draw its findings by comparing the results of the case studies with the literature review (analysis framework), thus making a comparison between what is known theoretically and what has been learnt empirically.

Chapter 3 also presents the collaboration matrix, a methodological tool developed to map and analyse the case studies. The chapter concludes by illustrating how the analytical framework described in Chapters 2, 4, 5 and 6 was created to provide a rationale for such comparison. It explains how it was drawn from existing literature about collaboration between designers and scientists (in order to help explain the designer's role, barriers and enablers, and contribution while collaborating with scientists), the nature of design work and scientific research (so as to help explain the collaboration process and its nature), and interdisciplinary studies (in order to ensure that all relevant/important aspect of collaboration are analysed).

As a result, the following Chapters 4, 5 and 6 explain these elements and enable the development of an analytical framework which is then used to compare evidence between case studies. They also conclude with a series of diagrams and tables that are later used in Chapter 9 to reflect upon the empirical findings of the case studies in relation to the research questions.

Chapter 4, “The Nature of Design Work”, explains that the nature of the designers’ work is fundamentally creative, and illustrates the design process as the main component of designers’ activity. It argues that the designers’ main preoccupation is to create functional entities and that their activity is interdisciplinary by default. It also summarises the core competencies of designers, grouping them into three categories: knowledge; attitudes and behaviours; and skills. The chapter also explores the types of collaborative engagements in which designers are normally involved. The chapter identifies different models that describe how designers can engage in collaboration. These models are based on parameters related to four questions: who initiates the collaboration, what is the role of the designer, what is the designer’s entry point in the project, and what is the designer’s involvement in the formulation of the design brief? Chapter 4 concludes with a diagram and a table, which will later be contrasted with evidence from the case studies. The diagram summarises the capabilities of designers, and the table presents various modes of design engagement as well as the different roles that designers can play whilst engaged in collaboration.

Chapter 5, “The Nature of Scientific Research”, outlines scientific research by arguing that there are two main dimensions that encompass scientists’ activity while conducting scientific research: the rational and the social. It also presents a discussion about the types and focus of scientific research. The chapter suggests that both basic research and applied research are linked to technological development. It proposes that the contribution of design might be different depending on whether or not the scientific research is geared towards technology or theory development. This chapter presents a diagrammatic model of the dimensions of scientific research and another of scientific research in relation to product development. The last one integrates the different purposes that scientific research can have: understanding principles, testing principles, applying principles or the development of applications. The two models are used to help explain, differentiate and map the role and contribution of designers in the different stages of scientific research based on findings from the case studies. They are also employed to identify the areas of scientific research to which designers can contribute.

Chapter 6, “Interdisciplinarity”, draws on existing literature on interdisciplinarity. It explains relevant models of interdisciplinary collaboration and identifies the potential barriers and enablers of interdisciplinary collaboration. The chapter argues that existing models of collaboration can be utilised to understand some aspects of collaboration between designers and scientists, but they might not be individually comprehensive or contextually suited to the particularities of collaboration between designers and scientists. However, the chapter proposes a new model that identifies three key categories for collaboration between designers and scientists in the context of scientific research: integration, project control and nature of the activity. This model is then used in Chapter 8 to understand the case studies and to identify different ways in which designers and scientists can engage in collaboration. Chapter 6 also identifies potential barriers and enablers of interdisciplinary collaboration. This is also used in Chapter 8 to compare it with the results of the case studies.

Chapter 7, “Case Studies”, presents a description of the three exploratory and two development case studies undertaken during this research. It also explains the collaboration matrix, which is a tool created to map and record the case studies. In this way, the work conducted by the designers and the scientists during collaboration, either when working separately or as a team, can be identified. This tool makes possible the visualisation of the stages of the collaboration, and helps to link project activities with design work and/or with scientific research. While further presenting the collaboration matrix, chapter eight also identifies an additional dimension of scientific research: the commercial. The chapter presents the case studies by explaining the motivation of the scientists and the designers for engaging in collaboration, and illustrates the issues addressed by the design team. It also shows how the design process took place in each case, how each collaboration was developed, and what the collaboration output was.

Chapter 8 presents the findings of this study. It compares the results of the cases studies with the analysis framework. It also positions each case study in relation to the process of scientific research and explains:

- How designers and scientists engage in collaboration
- The roles that designers can play in scientific research
- The nature of the designers’ contribution to scientific research
- The barriers to and enablers of collaboration between designers and scientists
- The areas of scientific research in which design can make an impact.

Concluding this thesis, Chapter 9 presents the conclusions of the study, identifying its contribution to knowledge with the support of several concluding diagrams and tables. The chapter also describes the limitations of the study in terms of scope and methodology. It highlights that case studies and participant observation have some inherent methodological challenges and limitations with regard to scope, validity and reliability, and how they have been mitigated. It also offers a personal reflection on the study, presenting thoughts resulting from it, and concludes by setting out a number of possible future research directions on the subject of interdisciplinary collaboration between designers and other professionals.

2. DESIGNERS AND SCIENTISTS COLLABORATING

This chapter explains how the existing literature on collaboration between designers and scientists identifies potential ways in which designers might contribute to scientific research, as well as the possible barriers to and enablers of collaboration. It also reveals that literature on the subject is scarce and mostly based on anecdotal or secondary evidence, and thus makes clear the need for further empirical research.

In order to start filling this gap, the chapter explores research on collaboration between designers and professionals of disciplines other than science. It shows that differences in assumptions between designers and other disciplines can affect their success as collaborators, and opens the question about how the fundamental assumptions and values of designers and scientists might affect their collaborative effort.

Finally, this chapter takes a slightly wider view by examining the literature on collaboration between artists and scientists. This illustrates how individual motivation, amongst other factors, plays an important role in the way that artists and scientists collaborate, and also how collaboration between artists and scientists is normally centred on artistic outputs rather than on scientific outputs.

The chapter concludes by setting the main research question "*How can product designers and scientists collaborate and, as a result, how might designers contribute towards scientific research activity?*"

This is followed by the proposal of a set of research sub-questions, all in the context of what is theoretically known about collaboration between designers and scientists. The chapter ends with a summary map of current knowledge about collaboration between designers and scientists, specifically about the former's contribution and role in collaboration with the latter, and about the barriers that can hinder such collaboration.

2.1 Designers collaborating

Design activity is collaborative by nature. Designers need to interact with different people at all stages of the design process. From initial contact with their clients until the delivery of a finalized prototype, designers team up with different people, for example with groups of users in order to develop initial concepts in a brainstorm session, or with teams of engineers to develop technical specifications of a product, or with technicians to decide on the best way of prototyping a design proposal. Erlhoff & Marshall [2008] explain how fundamental collaboration in design activity is: "*Designers today routinely work in teams, collaborating to create processes and products that reflect the different kinds of expertise amongst the team members—and designers who are not skilled as collaborators are increasingly unlikely to be successful*" (p. 65). Furthermore, design at its core creative stages of generating and developing concepts, which are often seen as the product of an individual designer's activity, is also often the result of a collaborative effort. As Lawson [2009] argues, "*the ideas in a design firm often emerge from a collaborative creative process, rather than from a single contribution*" (p. 188).

Although design activity tends to be collaborative by nature, it is apparent that little work has been carried out in relation to understanding how designers and scientists collaborate in scientific research. The lack of literature on this subject does not reflect the amount of currently known collaborative interaction between designers and scientists. For example, in the field of bioscience, there is a plethora of commercial, academic and institutional initiatives centred on this type of collaboration around the world. For example in Australia the "*SymbioticA*" project sets up collaborations between designers, artists and scientists in a university research context. SymbioticA claims to "*enabl(*e*) artists and researchers to engage in wet biology practices in a biological science department*"[4]. In the United Kingdom the project "*Material Belief*" teamed up designers and scientists with the purpose of "*moving scientific research out of the laboratories into public places*" (Beaver et al. [2009])[5]. In the United States the biologist Janine Benyus leads "*Biomimicry 3.8"*, a hybrid commercial-educational-community organisation based on collaboration between scientists and designers[6]. Biomimicry is inspired by nature, and attempts to use scientific knowledge on natural processes and structure to generate design solutions. In 2008 the ground-breaking exhibition *"Design and the Elastic Mind"* displayed more than 200 design objects and concepts developed in the last 25 years, from commercial products to objects of design for debate, all characterised by being the result of collaboration between designers and scientists. The exhibition took place in

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[4] (Symbiotica, University of Western Australia. http://symbiotica.uwa.edu.au/welcome)

[5] (Goldsmith University. http://materialbeliefs.com/)

[6] (Biomimicry 3.8. http://biomimicry.net/)

the Museum of Modern Art of New York, displaying design work that "*marries the most advance scientific research with the most attentive consideration of human limitations, habits and aspirations*" (MOMA [2008]).

Even though collaboration between designers and scientists is clearly much practised, noticeably few academic papers and books report cases of it. A notable exception to this is the work undertaken by Chris Rust in which he looks at different aspects of interdisciplinary collaboration between designers and scientists, identifying designer contribution to research and potential barriers to collaboration. This section will examine his work in detail, as well as a Gault & Kogan [2010] paper reporting on collaboration between designers and scientists. Their paper draws conclusions based on a series of interviews with designers and scientists engaged in interdisciplinary collaboration. The authors highlight the transformation of disciplinary boundaries in collaboration between designers and scientists, and the impact of designer's intervention on scientific research.

Looking at other possible sources of information on the subject of collaboration between designers and scientists, it is reasonable to think that research on collaboration between designers and professionals of disciplines other than science might also be useful in understanding the contribution that designers can make to scientific research. In the same way, literature that examines collaboration between scientists and artists can be also valuable. This section will examine all these different collaboration permutations, as illustrated in Diagram 2.1. In this way, comparisons can be made by placing either designers or scientists as the common denominator in collaboration.

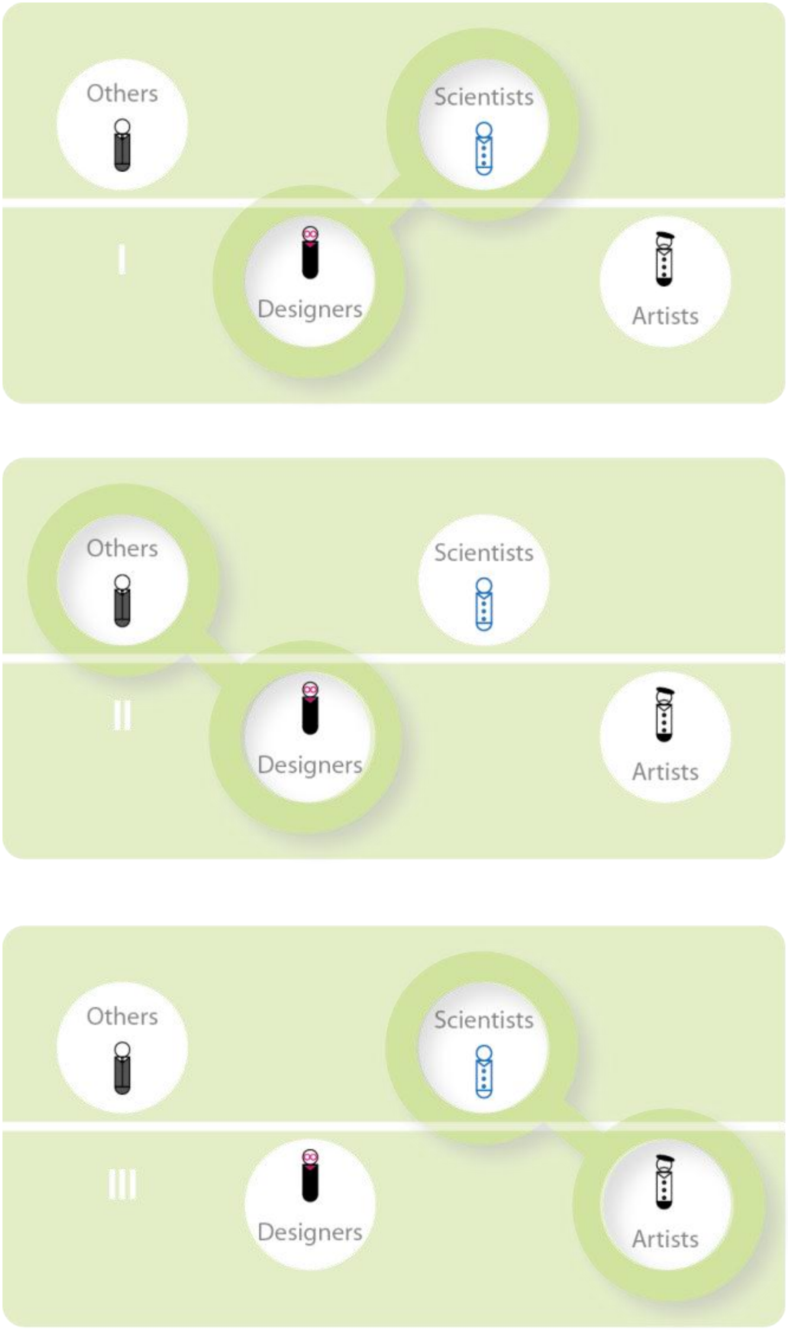

Diagram 2.1 *3 permutations for the analysis of designers and scientists collaborating: designers & scientists, artists & scientists, designers & other professionals from disciplines other than science*

2.2 Collaboration between designers and scientists

Gault & Kogan [2010] examine collaboration between designers and scientists by looking at their commonalities and differences. They argue that designers and scientists both "*share identical values such as innovation, creation of new products and knowledge*" (p.2), but they differ in the way that they relate to their "created objects". While designers and scientists both "surprise" with their creations, designers "seduce" with them and scientists "explain" with them.

Gault & Kogan [2010] also look at the function that drawings, sketches, models and 3-dimensional objects have as mediation resources or "tools" in designer and scientist collaboration. They argue that designers use these tools when collaborating with scientists as a means of explanation and persuasion. The tools open routes to dialogue and action. In addition, Gault & Kogan point out how designers can use these tools to emulate scientific thinking, by transcribing an opinion expressed by one of their interviewed scientists: "*The designer's drawings echo the scientist's experiments*". Conversely, the scientists appropriate these tools and use them to improve communication effectiveness with the designers. As a consequence of this, scientists can be perceived as designers. Thus, in this exchange of tools, disciplinary boundaries blur and designers and scientists affect each other's working methods and thinking. Gault & Kogan state that "*the seductive aspect of the designer's tools seems to become more demonstrative and scientific, whilst at the same time the scientist's tools evolve towards the seductive*". The authors see a commonality between the work of designers and of scientists, using Annie

Gentes' explanation of how both scientists and designers use a "creative mediation" process.

However, they qualify designers and scientists' approaches as complementary rather than equal. While designers "try to put technology into context", scientists "highlight its limits". Also, designers identify the contribution of scientists as filling gaps in their knowledge (or as the scientists themselves identifies as a "scientific token") whereas scientists describe designers' contribution as repositioning their scientific findings into a new context. The authors argue that "*The designer will not push the boundaries of a technology, but will put it in a context that will open up new frontiers for the researcher to study*". From this it is apparent that designers' interventions bring divergent rather than convergent thinking into scientific research.

Gault & Kogan's paper offers a very valuable range of ideas about collaboration between designers and scientists. It seems however that their contribution is limited to only two aspects of collaboration. On the one hand it examines disciplinary boundaries and on the other it explains how similar and complementary the designers' and scientists' approaches can be.

A different contribution to the subject of designers and scientists collaborating has been found in two papers written by Chris Rust [2004; 2007]. In his first paper, Rust claims that although scientific pursuit (discovery) is different from that of design (invention), it may be possible to initiate collaboration between both "traditions" which serves both of their aims. Rust proposes that the designers' abilities to "image new scenarios" and to create a "practical environment" and "experimental artefacts" may be useful for scientists in selecting or even generating routes of scientific enquiry. He states that there is a "creative dimension" in scientific research and that designers can contribute to it. Rust cites examples of collaboration between scientists and designers, and concludes that designers can contribute to scientific research by:

- Constructing models of representation and simulation that allow scientists to unlock their tacit or implicit knowledge. These are artefacts that can be collected and organised; they allow researchers to have a holistic view of their research process to perform a detailed review of their projects and to reflect on them, facilitating once again the use of tacit knowledge.
- Finding ways to apply scientists' underlying theories and to prototype ideas meeting the different project stakeholders' agendas.
- Developing prototypes that permit either quick or rigorous testing of ideas.
- Challenging scientists' perceptions of their data by being exposed to designers' representations, which can become a catalyst for new research routes or ideas.
- Producing models that free up tacit knowledge and stimulate new ideas.

Lastly, Rust highlights two barriers to effective collaboration with scientists:

- A poor "designer self-image": designers may think that their role within a scientific research project is not related to its core business (generating knowledge) and as result of this they can be relegated to a “subsidiary role”

- “Possible collaborators” may not recognise designers’ contributions.

Even though Rust offers an interesting perspective on interdisciplinary collaboration by identifying both opportunities and barriers to designers in collaborative research, he does not present empirical or first-hand evidence to support his claims. Although he reflects on research outputs and research methods, his study does not look at the specifics of interdisciplinary collaboration, or reflect on the experiences of the researchers in the context of interdisciplinary work.

In his most recent paper on this topic, Rust [2007] reflects on how creative disciplines (art and design) can contribute to scientific research. Emphasising that designers may be better suited to undertaking research activities than artists are, Rust argues that “*the concept of investigating/evaluating the outcomes of their work is embedded in the culture of many design disciplines*”. Amongst other examples, Rust presents a collaborative project between a design group composed of a filmmaker, a product designer, and a group of scientists. Their collaboration aims to develop video material that communicates to the public certain “molecular actions of nanotechnology”. Rust offers an explanation as to how it is necessary to create visual metaphors that the general public can understand. At the same time these visual metaphors ought to “remain true to the physicists’ scientific understanding” of the phenomenon. The author points out the communication difficulties the participants had due to the lack of “any shared formal language”. He concludes his paper by outlining “tentative principles” for interdisciplinary research between creative people and scientists:

- Some research outcomes can be valid but not easily recognised or stated by the researchers.
- Some contribution to research can be “generative” and not necessarily “specific”. “Generative” in the sense that creative people can contribute to research with material that helps scientists to take their research in new directions, and non “specific” in the sense that creatives shouldn’t make “strong judgements” about how “significant” their findings are for the research.
- Regardless of the type of contribution made by creative people and of how intentional and purposive it is, only the “audience can determine” what is relevant.
- Methods of creative research reveal “tacit” knowledge, but also tacit knowledge is used to shape those methods.
- In order to be recognised as researchers, artists and designers should: Specify their research subject and their motivation; Show a good understanding of their research state of affairs (past and present) in their subject of study; Make use of an appropriate research method; and be able to communicate their findings to the wider community.

Although Rust has a good insight into what can be perceived as an inexplicit or tacit contribution by creative people to research, a substantial part of the evidence that supports his claims (personal conversations with artist and designers), is not presented or accessible. At the same time, it is noticeable that conclusions have been mainly drawn from the views of the participant designers; the conclusions could have been different had the views of the scientists been considered to a greater extent. Rust also claims that there are differences between artistic and designer contributions, but no explicit details of these differences are presented.

To summarise Rust's view, it may be concluded that designers can contribute to scientific research in different ways by:

- Unlocking "tacit" knowledge
- Connecting scientists with the non-scientist, and helping to disseminate scientific knowledge amongst the general population
- Facilitating the advancement of scientific research, by providing means of experimentation and reflection
- Challenging scientists' perceptions and encouraging the pursuit of new research directions.

It can also be concluded that the designer's role in scientific research can be defined by the task they are asked to perform (the role-task). This includes:

- Constructing models of representation and simulation
- Designing artefacts for testing and experimentation
- Ideating scenarios

- Finding applications for scientific research outcomes
- Visualising scientific ideas.

2.3 Designers collaborating with professionals of disciplines other than science

Examining research on collaboration between designers and professionals of disciplines other than science can be useful in understanding the potential contribution that designers can make in scientific research. Two examples of this type of collaboration have been selected to highlight interesting aspects of the work.

The first example looks at collaborative work between designers and engineers. In a study that included a review of literature on communication theory and interdisciplinary product development, as well as an empirical ethnographic study in an industrial environment, Persson & Warell [2003] examine different aspects that influence collaboration between industrial designers and engineering designers.

First, the authors draw attention to the organisational settings of collaboration between engineers and designers. They emphasise that late involvement of designers in projects can hinder communication. They also identify physical separation between designers and engineers as an obstacle to collaboration, and stress that a lack of definition in communication channels and reporting structures can affect collaboration.

Persson & Warell also explain that differences in the specialist vocabularies of designers and engineers are an obstacle to collaboration. They say that engineers have difficulties in understanding the “fuzzy” vocabulary of designers and that the designers do not understand the language used by engineers in their technical specifications.

The authors comment on the different means of communication that both disciplines employ. While engineers tend to use “verbal models” and bi-dimensional technical drawings, designers are more inclined to use tri-dimensional computer models and renderings, pictures and hand sketches. Persson & Warrell emphasize that this dissimilarity affects both engineers’ and designers' ability to understand how compatible their respective ideas are, since none of these methods of representation are capable or representing all of the features of a design.

The authors highlight that designers and engineers have different approaches to problem solving. While engineers focus on addressing “sub-problems”, designers have a more “holistic” view. Equally, engineers base their solutions on known existing devices, whereas designers strive for “innovative or unusual solutions”.

The authors comment on Muller’s [2001] observation that designers prefer to “keep concepts open ended” for as long as possible. This, combined with the different views of design problems of designers and engineers, can become an obstacle to planning and timetabling.

They also draw attention to the conflict arising from designers' and engineers' diverse project focus. While designers focus on values of "social and cultural utility", engineers look for material utility. Also, designers use "their own subjective knowledge, personal views and values" to solve problems, while engineers resort to validated scientific information and the scientific method. To summarize, Persson & Warell identify the following areas of difficulties in collaboration between designers and engineers:

- Collaboration settings (physical and organisational)
- Communication (vocabulary and tools)
- Approach and methods
- Focus and epistemological/ontological stance

The second example examines collaborative work between designers and anthropologists. Here Dawson [2002] bases his observations as a participant in a multidisciplinary team, collaborating in two different design firms, presenting the disciplinary differences that characterise collaboration between designers and anthropologists.

Dawson discusses that the communication between designers and social scientists is affected by "fundamental assumptions held by each discipline". He argues that while "*the anthropologist is taught to seek the status quo of the material world around us*", the product designer "*actively seeks ways to change it and improve it, whether the target user realizes it needs improvement or not*". The author also makes clear that the roles of both disciplines are well defined within the design consultancy environment. On one hand, anthropologists are responsible for ensuring that the consumer's voice drives the projects; on the other, designers are required to develop innovative and desirable products. In short, anthropologists are commissioned to understand the material world and designers to change it.

The author explains that designers are "visual" and use sketches as a fundamental communication tool, whereas anthropologists are text-based. However, anthropologists also work with sketches (but written ones). The differences between these two kinds of sketches relates to their accessibility. Visual sketches are made to be understood and accessed, and to be immediately useful as a development tool. Text sketches used by anthropologists are "representations of things to come" and are not accessible. Text sketches need to reach the stage of semi-complete analysis to be understood and therefore useful. This creates a problem in collaboration and in the project rhythm. The material produced by anthropologists is often "too much information for designers" and requires adjusting to fit into project times in design consultancies.

Dawson comments on the "image boards" used by designers as a research, inspiration and communication tool. The author portrays these image boards as hindering the main task of anthropologists in collaboration with designers. This task is trying to capture the "valid *voice*" of the consumer. Dawson argues that by using these boards, designers build up images of consumers' values and motivations "on their behalf" rather than from "real insight". This outlines the main barrier that affects collaboration between designers and anthropologists: while many designers base their work on their own perceptions of what people’s problems might be, anthropologists try to elicit these problems directly from consumers.

There appear to be similar barriers to successful collaboration between designers and engineers as between designers and anthropologists. For example, a designer’s distinctive way of communicating through two-dimensional sketches contrasts with the technical drawings of engineering or the written material of anthropologists. The designers’ pragmatic and subjective approach distinguishes them from the engineers’, which is rational and methodical, and from the anthropologists’, which is deep and reflective. It seems that the differences between the participants’ fundamental assumptions and values can be a more significant obstacle in these cases than in collaboration between designers and other disciplines. For example, while engineers are driven by rationality, processes and scientific data, designers are more intuitive, less structured and tend to rely on their own views and opinions while taking professional decisions. Anthropologists proceed rigorously and methodically, in contrast to designers’ pragmatism and flexibility.

2.4 Collaboration between artists and scientists

Studies that look at collaboration between artists and scientists can also serve as a reference for understanding collaborative interaction between designers and scientists, since solving problems is an important part (but not the only part) of design activity. Crilly [2010] argues that "*many studies of creativity examine the work of artists and scientists in an attempt to uncover the cognitive processes that are common to both. Such studies seldom make reference to design, but like design, both artistic creativity and scientific discovery can be considered as problem solving activities*" (p.4). However, designers and artists are different in many respects and the nature of their collaborative efforts with scientists may be also very different. Due to the similarities between artists and designers, special care needs to be taken to understand which aspects of collaboration are related to the particular characteristics of designers and which are not. As Hafner claims (cited in Crilly 2009), "*while distinguishing artists from scientists is an intuitively obvious thing to do, doing so with any precision is a difficult task because each requires a combination of knowledge and skill, each proceeds through processes of creation and discovery, each is sustained by aesthetic and structural sensitivities, and each demands discipline while benefiting from fortune*".

Although collaboration between artists and scientists is widespread across the globe, academic work that looks at interdisciplinary collaboration between artists and scientists is hard to find. Shanken [2005] argues that "*there is scant metacritical research that studies best practices, working methods and contextual support and hindrances*" p. 417. However, the available literature is useful to help understand some important aspects of collaboration such as motivation, contribution, barriers and outcome focus.

Artists' involvement in interdisciplinary collaboration with scientists can be motivated by their interest in using science and technology as the medium through which they produce art; in this case, they instrumentalise science, employing it as a means for artistic production. As Hauser [2008] explains, this is "*art that utilizes biotechnology but does not necessarily address thematically linked issues*." Artists can also focus their work on science related issues by incorporating scientific imagery or techniques or by letting their artistic creation be inspired by or reflect on science; in this case science becomes the subject of their artistic production. This is the case with bio-artists, in whose work the use of "*biological metaphors and symbols serves to fuel biopolitical discussion and which can get along fine with conventional techniques*" (Hauser [2008] p.84). As a result of this, artists collaborating with scientists can have an impact on the public perception of science: artistic output can foster "*questions about development in science and technology, and the stories by which science comes to be "appreciated" by society*" (Mayeri [2008] p. 80).

It appears that artists' inclination to interact with scientists is motivated by a genuine interest in research (as a tool or as a subject). In contrast, as Shanken [2005] suggests, scientists collaborate with artists for other reasons. They may collaborate to "enrich their public image by an association with the arts" or to redeem a stained public image of the business they work for. Shanken also suggests that scientists may be interested in using artistic collaborative work to "communicate abstract and complex scientific concepts to broader audiences", especially those associated with public debate or to research that uses public funding, and has no foreseeable output or application.

Shanken [2005] p.416 also outlines another aspect that characterises collaboration between artists and scientists: it needs to be supported "from within institutional frameworks". He also suggests that this support mainly occurs when there is a subject from the science side (either in industry or academia) who has a personal conviction in the project.

It emerges that collaboration between artists and scientists is formed by an addition instead of an integration of disciplinary interests. It is also apparent that collaborations between artists and scientists are not motivated by research needs (especially on the scientists' part) but from institutional or particular individual interests.

EVL (University of Illinois Electronic Visualization Laboratory) director Dan Sandin describes artists' and scientists' contributions to collaborative engagement by stating that "*artists offer their knowledge, communication-design and project-management skills. Scientists provide the content and design challenge and the means to raise money to give artists access to high-end technologies*" (cited in Pearce et al. [2003] p.124).

Similarly, Pearce et al. argue that artists contribute in art-science collaboration by:

- Providing lateral thinking about technology and science
- Socializing and humanising technologies
- Challenging dominant structures in this process
- Engaging in actual invention

It seems that the type of contribution that artists can make in collaboration with scientists is similar to that which designers can make. However, it remains to be seen if designers will "challenge dominant structures in the process" as artists apparently do.

Pearce et al. [2003] (p.125) reports that possible barriers to collaboration between artists and scientists are the use of different disciplinary languages and the lack of disciplinary recognition and reward career structures for scientists or artists engaged in interdisciplinary research. Although the language barrier has also been identified as a problem in collaboration between designers and scientists, the lack of career reward for interdisciplinary engagement has not.

One last feature of the collaboration between artist and scientists is that it tends to be centred on artistic output. As Barnett & Whittle [2006] point out, "*the main focus of science/art collaborations often lies within the world of art rather than science*". This may be different to what would happen in collaboration between designers and scientists. Further research that provides empirical evidence is needed to confirm this.

Tables 2.1 and 2.2 summarise the main findings of existing literature regarding collaboration between designers and scientists. They show the different potential contributions of designers to research, identify the roles or tasks that designers are set to develop while collaborating with scientists, and recapitulate the main potential barriers to a successful collaboration. For this last point, Table 2.2 groups the barriers according to the categories set by Pearce, as previously explained in this chapter.

These tables will serve as a point of reference to identify the findings of this thesis, and its contribution to knowledge.

Summary of Designers' Contribution and Role in Collaboration with Scientists

		CR	G&C	P	P&W	D
Designers' Contribution	Unlocking "tacit" knowledge	•				
	Connecting scientists with the non-scientist, and helping to disseminate scientific knowledge amongst the general population	•				
	Facilitating the advancement of scientific research, by providing means of experimentation and reflection	•				
	Challenging scientists' perceptions and encouraging the pursuit of new research directions	•				
	Repositioning of scientific findings into a new context		•			
	Bringing divergent thinking (Contrasting convergent)		•			
	Bringing disciplinary knowledge			◎		
	Bringing communication, design and project management skills			◎		
	Providing lateral thinking about technology and science			◎		
	Socialising and humanising technologies			◎		
	Challenging dominant structures in this process			◎		
	Engaging in actual invention			◎		
Designers' Role-task	Constructing models of representation and simulation	•				
	Designing artifacts for testing and experimentation	•				
	Ideating scenarios	•				
	Finding applications for scientific research outcomes	•				
	Visualising scientific ideas	•				

Concluded from collaboration between: Designers & Scientists ▷ • Designers & other disciplines ▶ ◉ Artists & Scientists ▶ ◎

CR: Christ Rust (2004, 2007) G&C: Gault & Kogan (2010) P: Pearce et al (2003) P&W: Persson & Warell (2003) D: Dawson (2002)

***Table 2.1** Summary of Designers' Contribution and Role in Collaboration with Scientists*

Summary of Barriers for Collaboration between Designers and Scientists

Barriers for Collaboration

	CR	G&C	P	P&W	D
Attitudes					
A poor "designer self-image" leading him/her to be relegated to a "subsidiary role"	●				
"Possible Collaborators" may not recognize designers' contributions.	●				
Lack of disciplinary recognition			◘		
Approach and methods					
Different approach to problem solving				◙	
Different methodological approach (intuitive/subjective vs. Scientific rational and objective)				◙	
Focus and epistemological estance					
Project focus divergence (what is important)				◙	
Disciplinary assumptions (status quo vs change)					◙
Communication (vocabulary and tools)					
Different disciplinary language			◘	◙	
Different ways and styles of communication e.g visual vs. written.				◙	◙
Communication difficulties the participants may have due to the lack of "any shared formal language"	●				
Collaboration settings					
Physical separation between collaborators				◙	
Lack of definition of communication channels				◙	
Lack of a reporting structure				◙	
Late entry point into the project				◙	
Lack of a reward career structure			◘		

Concluded from collaboration between: Designers & Scientists ▷ ● Designers & other disciplines ▶ ◙ Artists & Scientists ▷ ◘

CR: Christ Rust (2004, 2007) G&C: Gault & Kogan (2010) P: Pearce et al (2003) P&W: Persson & Warell (2003) D: Dawson (2002)

Table 2.2 *Summary of Barriers to Collaboration between Designers and Scientists*

2.5 Summary and implications

This chapter summarises the findings of the main studies regarding collaboration between designers and scientists; between designers and professionals of disciplines other than science; and collaboration between scientists and artists.

Designers' intervention in scientific research can open up new areas of study, and the nature of designers' and scientists' tools and methods may be complementary. Designers can have a meaningful role in collaborative work with scientists by creating material or conceptual devices for scientific research (e.g. experimental instruments or ideating scenarios). Through these devices, designers contribute to scientific research in a variety of forms, such as unlocking tacit knowledge or providing means of experimentation. The chapter also explains that when designers collaborate with professionals from disciplines other than science, obstacles appear mainly from differences in fundamental assumptions and values.

Additionally, the chapter argues that an artist's collaboration with scientists is characterised by the dissimilitude in their motivations. While artists seem to have a genuine interest in the research topics, scientists get involved on behalf of companies that seek to be associated with artists in order to improve their reputation and public image. It also seems that collaboration between artists and scientists focuses mainly on artistic output. It is apparent as well that artists' contribution to scientific research is similar to that of designers, and is hindered by similar barriers. However, it seems that collaboration between artists and scientists is affected by the lack of a rewarding career structure that stimulates such endeavour.

It can be concluded that the existing literature identifies important aspects of collaboration between designers and scientists, especially regarding the type of contribution that designers can offer in collaboration with scientists and the barriers to this type of collaboration. However, empirical studies are rare, and thus there are still a number of gaps in knowledge about this collaborative relationship. For example, there is little evidence about the possible ways in which designers and scientists can engage in collaboration. Moreover, there are few attempts to comprehend what enables collaboration between designers and scientists or, indeed, to understand the process of collaboration itself. There is also little evidence about what stages of scientific research are most likely to be positively affected by designers' contributions, or about what might be the role of designers in answering scientific questions in the context of scientific research.

In addition to this gap in knowledge, it is also noticeable that most of the evidence that supports existing research is based on anecdotal or secondary information. To date, no case study has been published that explicitly aims to observe and understand the particularities of collaborative efforts between scientists and designers. This clearly indicates that further study is needed to present primary empirical evidence. Such research needs to look at the views of both designers and scientists, to help provide new insight into the subject and perhaps uncover further contributions by designers to scientific research.

It should also investigate if interdisciplinary collaboration between designers and scientists should be focused on scientific output or on design output. Thus, this thesis seeks to find an answer to the question *"How can product designers and scientists collaborate and, as a result, how might designers contribute towards scientific research activity?"*

In particular this research intends to address the questions:

- *What possible forms of collaboration can take place between designers and scientists in the context of scientific research?*
- *What is the role that designers potentially have in scientific research while collaborating with scientists?*
- *What is the nature of the contribution that designers can offer to scientific research?*
- *What are the barriers to and enablers of such collaboration?*
- *What are the areas of scientific research in which designers can make an impact?*

3. RESEARCH APPROACH AND METHODOLOGY

As stated in the previous chapter, this research intends to offer an answer to the question "*How can product designers and scientists collaborate and as a result how might designers contribute towards scientific research activity?"*

In order to answer this question, this research seeks to outline *possible forms of collaboration between designers and scientists*, to identify *the role that product designers potentially have in scientific research while collaborating with scientists*, and to make evident *the barriers to and enablers of* such collaboration. The research also tries to identify *the nature of the contribution that product designers can offer to scientific research*, and to indicate those *areas or activities of scientific research in which product designers can intervene*. In broader terms, this research has been undertaken in order to understand what, how and why collaboration between designers and scientists occurs.

The objects of enquiry of this research (forms of collaboration, roles, barriers and enablers, the nature of contribution and the areas of scientific research) are all human constructs subject to interpretation. Furthermore, they are notions that only acquire specific meanings when they are set in specific contexts, enacted and interpreted by people. This research seeks to understand the interdependence between these notions, the context of scientific research and designers and scientists collaborating.

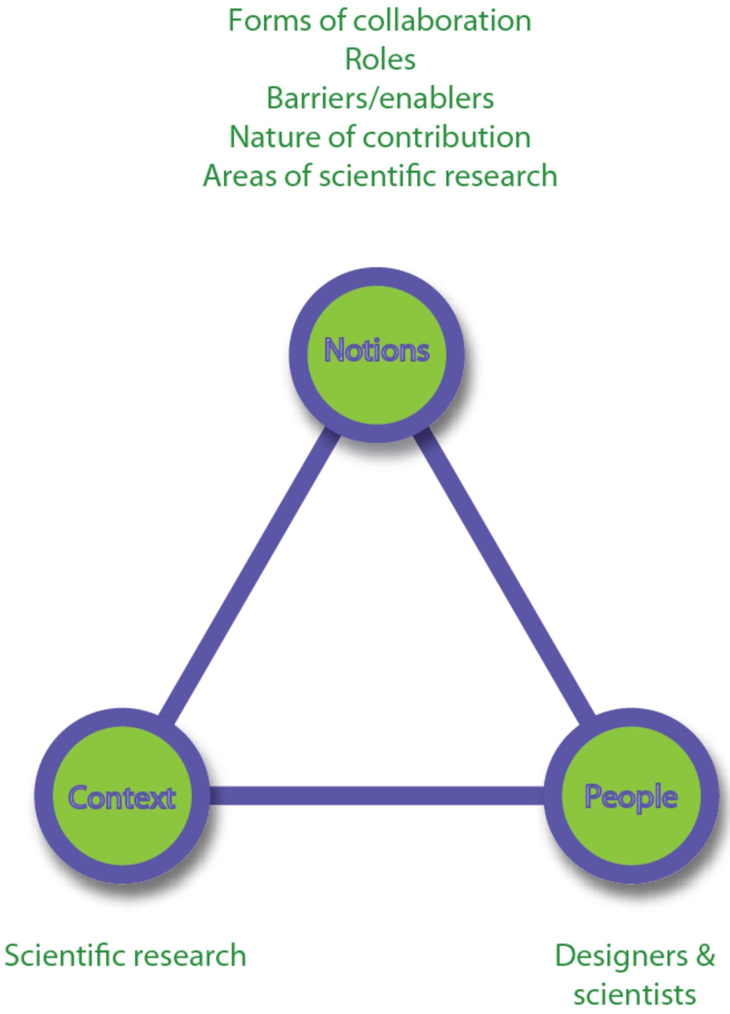

Diagram 3.1 *Interdependence between the research notions, the context in which it happens and the people involved*

3.1 Philosophical approach

This research study subscribes to the qualitative research paradigm, as it regards its object of analysis as the product of interpretation, focusing on meaning (Robson [2011], Flick et al. [2004]). In this research these meanings are considered as constructions of reality that come from the descriptions and views of participants and researchers (Robson [2011]; Guba & Lincoln [1994]; Flick et al. [2004]). Hence, this research agrees with the importance of the values of participants and researchers (Robson [2011]) as they influence their world views and descriptions.

As this research understands that the social world and reality are created by the people involved (Robson [2011]; Flick et al. [2004]) it recognises that people's behaviours and attitudes are influenced by the context they live in, and therefore phenomena need to be understood in their settings and context (Robson [2011]; Guba & Lincoln [1994]; Flick et al. [2004]). This research seeks to understand the interrelations between context and people, and has as its epistemological principle the understanding of complex relations (Flick et al. [2004]).

Other aspects of this research reinforce its positioning within the qualitative research paradigm. For example it embraces subjectivity as a means for making objective life circumstances relevant, and sees objectivity as a barrier between researchers and participants (Robson [2011]; Flick et al. [2004]). Also, it uses a flexible research design that emerges as the research is undertaken (Robson [2011]). Additionally, it uses inductive logic to make ideas emerge while or after data is or has been collected (Robson [2011]).

Amongst competing qualitative paradigms, this research takes a constructivist stand as it coincides with the idea that "*knowledge in some area is the product of our social practices and institutions, or of the interactions and negotiations between relevant social groups*" Gasper [1999]. This research also assumes that knowledge on the subject of collaboration between designers and scientists needs to be at least partially generated from the researcher’s own interpretation of social interaction (the other part may come from the studied subjects’ own interpretation), as this constitutes reality. Hence, the researcher’s own subjectivity becomes an integral part of the construction of reality. As Robson [2011] explains, in constructivist research the “*values of the researcher and others are assumed to exist and subjectivity is an integral part of the research*”. Denzin & Lincoln’s [1994] comparison of qualitative inquiry paradigms suggests that in a constructivist approach realities are “*mental constructions…socially and experientially based, local and specific in nature” and are “dependent for their form and content on the individual persons or groups holding the constructions*”. The authors also explain that the ontological nature of those constructions is “*not more or less true*” but “*simply less or more sophisticated*”. This is of special relevance to this study, since it coincides with the idea of seeking a richer description and a more refined interpretation of collaboration between designers and scientists than has been conducted in previous work. Also, as in this study the researcher is a design practitioner, this enables richer conclusions to be drawn than by independently observing a phenomena as a “novice”.

Denzin & Lincoln [1994] also comment that in a constructivist approach, research findings are “*literally created*” as the research advances from the interplay between the “*investigator and the object of investigation*”. This reflects the approach of the present study in which the interaction of researchers with designers and scientists generates concepts and ideas.

This body of ideas and concepts is then analysed and synthesised to become the findings of this study.

Finally, Denzin & Lincoln emphasise the dialectical nature of the constructivist approach methodology. They highlight the interpretative character of the constructivist research methodology, arguing that new knowledge is consensually generated in a dialectical manner (through a dialogue between researcher and researched). In this research, previous knowledge on collaboration between designers and scientists will be reviewed and complemented by new insights from the interaction of scientists and designers in their social setting.

3.2 Research approach

This research has taken case study as its core research approach. In doing so, this research adheres to the idea of considering case study not as a simple technique for data collection, but as something more comprehensive that encompasses strategic and methodological aspects of the research. This view takes elements from different authors who look at case study as strategy, methodology and form of enquiry (Yin [2003]; Creswell [2007]; Woodside [2010]).

Case study inquiry enables the exploration of phenomena occurring in its settings, and access to the perceptions of the people involved in these phenomena. This in turn enables researchers to understand how and why the phenomena occur. In effect, access to designers and scientist while collaborating is essential if the researcher is to understand their interactions, to listen to their perceptions, their explanations and their views, and from these to draw conclusions and induce explanations. As Yin [2003] argues, case studies are "the "*preferred strategy when "how" or "why" questions are being posed, when the investigator has little control over events, and when the focus is on contemporary phenomenon within some real-life context*".

The subject of study of this research, collaboration between designers and scientists in the context of scientific research, seems to exemplify an occurrence in which phenomenon-contexts are blurred. Contextual elements such as the culture and social setting in which collaboration takes place can greatly influence the ways in which it happens. Case study inquiry makes it possible to examine phenomena in their social and cultural settings, enabling the researchers to understand them in their complexity and mutual relations. As Yin explains, case study inquiry serves to *"investigate a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident."*

Furthermore, Gillham [2000] suggests a point to help establish whether case study is an appropriate method for the study of a specific subject. He argues that if the object of study is *"a unit of human activity embedded in the real world…which can only be studied or understood in context…which exists in the here and now…(and)…that merges in with its context so that precise boundaries are difficult to draw"* then case study is an appropriate method of study. As collaboration between designers and scientists is a human activity of the type described by Gillham, then case study seems to be a valid and suitable method for this research.

There are other qualitative approaches that could have been used for this study but they were not deemed entirely suitable, for a range of different reasons. These approaches include Ethnographic studies, Phenomenological studies and Grounded theory.

Although an ethnographic approach is suited to the study of real situations, it is mainly oriented towards the investigation of cultural aspects of a group or group behaviour. Ethnography deals with the "*description and interpretation of the shared patterns of culture of a group*" Creswell [2007] p.78 and has the goal of creating a "*cultural portrait of a group*" (Hancock & Algozzine [2006] p. 9). This strong focus on cultural aspects makes the ethnographic approach less suitable for this research, since it seeks a more holistic understanding of reality instead of focusing only on cultural aspects. Additionally, an ethnographic approach would need access to "real situations" in which collaboration between designers and scientists takes place, so they can be studied by a researcher. However, exciting cases of current collaboration between designers and scientists were unavailable at the onset of the research, and therefore the case study approach was deemed more favourable.

Phenomenological studies are useful for research on a specific phenomenon through the lived experiences of several people (Hancock & Algozzine [2006]).

However its main assumption is that there is an “essence” or central meaning of these experiences to be investigated (Hancock & Algozzine [2006]; Creswell [2007]). This does not coincide with the purpose of this study which seeks to explore different aspects of the collaboration phenomenon, rather than seeking to find a single central ‘meaning’. The phenomenological approach coincides with the constructivist approach of this research regarding the idea that the “*existence of objects of analysis that we think of as real*” are “*the product of our own interpretation*” (Smith [1998] p.161). However, this approach may rely on finding past cases and interviewing the protagonists. But they are few, and any interviews would generate after-the-event recollections. These would not be as informative as following a live case study.

Grounded theory looks to uncover a theory that is “grounded” in the data (Hancock & Algozzine [2006]; Creswell [2007]). This research approach is not considered suitable, since the purpose of this study is to describe and to analyse for understanding, rather than to form a definite theory about the object of study. Using grounded theory would involve interviewing participants in existing or previous cases in order that theories or models explaining a phenomenon might be developed from the data. But, this research tries to describe rather than explain. Also, there are not sufficient previous cases available.

3.3 Data collection

In this research, consideration of the best method for data collection has focused on two main aspects: first, the type of data that are deemed important, and secondly a series of practical considerations around the collection of this data.

Regarding the first aspect, it was important to have direct, first-hand access to the interaction between designers and scientists while collaborating, as well as to their views and thoughts. This seemed to be fundamental for the identification and exploration of the key themes of this inquiry: roles, barriers and enablers, the nature of contribution and the areas of scientific research.

As a consequence of this, participant observation was chosen as the main data collection method for this research as it "*gives privileged access to meanings through the researcher's empathetic sharing of experience in the worlds he or she studies*" (Platt [2001] p.144). According to Yin [2003] (p.14) participant observation has also other advantages which in turn are potentially useful for this research. First, it gives the researcher the "*ability to gain access to events and groups that are otherwise inaccessible to scientific investigation*". For example, as the researchers become part of the collaboration team, they are guaranteed unrestricted access to all of its potentially meaningful events, such as briefing meetings or brainstorms sessions. Secondly, the researchers can develop the "*ability to perceive reality from the viewpoint of someone "inside" the case study rather than external to it*" (p.14). As the researchers in their role of participants are "living" all the experiences, but can (and should) be able to also look at them as an outsider, they can develop a holistic view of the studied phenomena by integrating both their views as an insider and external observer. Finally, researchers as participant observers might be able to "*manipulate minor events, such as convening a meeting of a group of persons in the case study. The manipulations will not be as precise as those in experiments, but they can produce a greater variety of situations for the purposes of collecting data*".

Some practical considerations also influenced the choice of participant observation as the main data collection technique. First, the fact that the researcher was also a product designer made participation as the "designer" in the case studies viable. Had not this been the case, participant observation might have not been an option since it would have been expensive and impractical. Second, gaining access to teams of designers and scientists in commercial/industrial environments or in other universities (perhaps using non participant observation to collect data) was considered difficult within the time and budget constraints of the research; not least because examples of this type of collaboration are extremely rare. Thus, pursuing and obtaining access to these kinds of settings would have taken an unreasonable amount of time and effort, and may not have resulted in the identification of suitable case studies. Thirdly, having a design capability within the research team becomes a trading tool with which to negotiate and obtain access to scientists and scientific settings. By being able to approach the scientists with something to offer on exchange for their participation, the researcher was more able to find suitable case studies. Lastly, the potential availability of a wide range of scientists with a potential interest in collaborating with designers within the university, made it easier to identify case studies and use participant observation. Potential issues of intellectual property, legal protection, insurance and contractual negotiations, as well as aspects related to communication, organisational culture, geographic location, etc., which potentially could have hindered the research process, were addressed under the university umbrella.

In all cases, observations were made in the form of notes, tape and video recordings taken during meetings and work sessions. Initial and follow-up semi-structured interviews with the participant scientists were audio recorded and a physical collection of cognitive artefacts (designers' sketches, models, prototypes, etc) and design outputs was undertaken. Follow-up discussions were systematically carried out immediately after each meeting, presentation and work session. Written case reports were produced and the collaborating scientists were invited to comment and check for any discrepancies in the researcher's account of the case studies.

All data collected was classified by case study and kept in a digital database only accessible to the research team, as well as written notes, sketches and drawings, which were filed chronologically in folders. Physical design output (models and prototypes) was kept by the scientists.

Previous to the beginning of each case study, the research team informed the participant scientists about the purpose of the research and why they were interested in collaborating with them as a case study. Also, it was explained to the participant scientists that they would be observed and recorded during the case studies, and would be ask to participate in pre- and post-case study interviews.

During the data collection and other stages of the research, the main ethical issue arising related to intellectual property. Regulations within the university governed all intellectual property generated during the case studies, including the regulation on IP subject to third party agreed terms, to comply with the research funding body (EPSRC) IP regulations. However, no agreement was promoted to clarify designers and scientists' share of the IP of ideas/output arising from the case studies. Although there were no disputes in any of the case studies, the research group identified potential issues on this subject, and found it advisable to clarify this at the beginning of future collaborative projects.

3.4 How the research was conducted

The research was structured in four stages:

- Phase 1 Literature review (Analysis framework)
- Phase 2 Case studies (Data collection)
- Phase 3 Collaboration matrix/findings generation (Data Analysis)
- Phase 4 Report writing (Data Synthesis)

These phases were mostly sequential but they overlapped and ran in parallel on occasions. For example the literature review, which was the centre of the research activity at the beginning of the project, continued with lower intensity during all stages until the end. In practice, data analysis activities started almost simultaneously with the case studies and were carried out in parallel. Similarly, the analysis and synthesis data stages occurred simultaneously in several occasions. For example, the study findings were generated while the report was being written.

Diagram 3.2 offers an overview of the research phases and how they are interconnected. It also shows the research output at different stages.

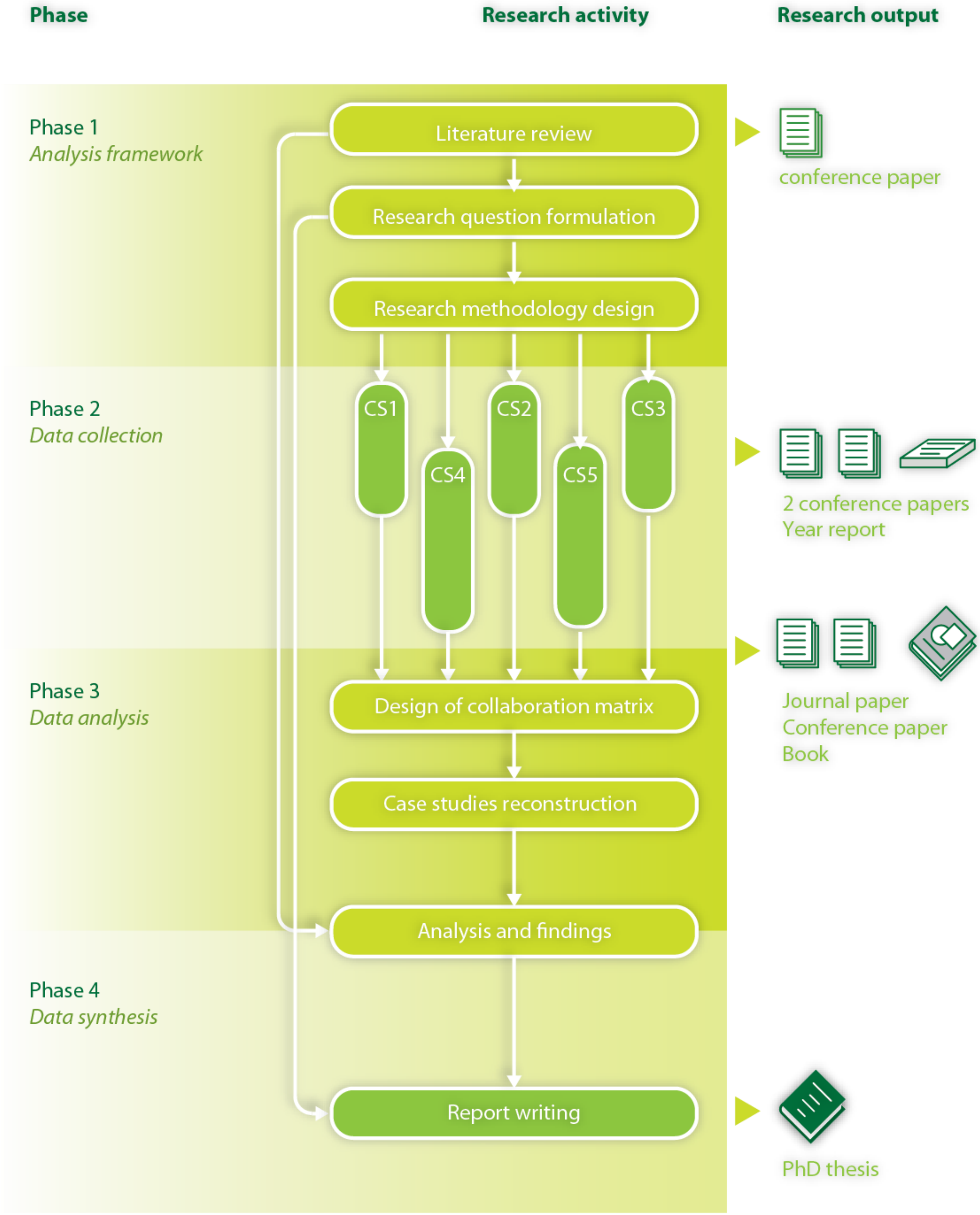

Diagram 3.2 *Research phases, activities and output*

3.4.1 Phase 1 Literature review

In phase one, the literature was reviewed with the purpose of understanding the extent of existing knowledge on the subject of collaboration between designers and scientists in scientific research. The literature review was carried out using online resources such as:

- Academic search engines: EBSCO, Scopus, Science Direct, Academia.edu, etc
- Academic publishers' online databases: Springer, JSTOR, Taylor & Francis, etc
- Online public search resources: Scribd, Free PDF Search Engine, Google books, Google scholar, etc.

Also, the library databases of Cambridge University and of Central Saint Martins College of Art and Design were consulted. Additionally, an initial search was made by writing to the online JISCMAIL PHD-DESIGN list.

Papers and books were searched using relevant key words such as:
Design, science, designer, scientist, interdisciplinary, multidisciplinary, collaboration, cooperation, technology, scientific research, design process, research method.

Papers' and books' bibliographies were also reviewed as a method of finding other related papers and books.

Relevant papers were selected and printed. The hard copies were filed and grouped in several categories to make consultation easier:

- Science and scientific research
- Collaboration in science
- Design and design process
- Design and science
- Designers collaborating with people from other disciplines
- Art and science collaboration
- Interdisciplinarity.

The papers were also classified and filed electronically using the software EndNotes and the online resource Delicious, and kept as PDF files.

The literature review looked at three different relevant areas: Design, Science and Interdisciplinary Studies. From the Design area, this study drew conclusions from existing knowledge about designers collaborating with scientists and with other professionals of discipline other than science as presented in Chapter 1 of this thesis. This was also complemented by studies that examined collaboration between artists and scientists. Literature on the Design area also served to compare designers and scientists as members of different disciplines as presented in Chapter 3, and to explain the nature of design work as shown in Chapter 4.

The literature review of the Science area was fundamental to describe the nature of scientific research as illustrated in Chapter 5, and also served to compare designers and scientists as shown in Chapter 1.

Finally, as collaboration between designers and scientists can be an example of interdisciplinarity, literature was reviewed in the area of Interdisciplinary Studies. This was used to explain models of interdisciplinary collaboration, as well as barriers enablers of collaboration, in Chapter 6.

The literature review generated two main outcomes. First, it helped to identify a research gap, making evident the need for empirical evidence to corroborate and complement existing knowledge on the subject; and secondly, it served to formulate the research question.

Diagram 3.3 synthesises how each area of the literature review contributed to specific chapters of the analysis framework.

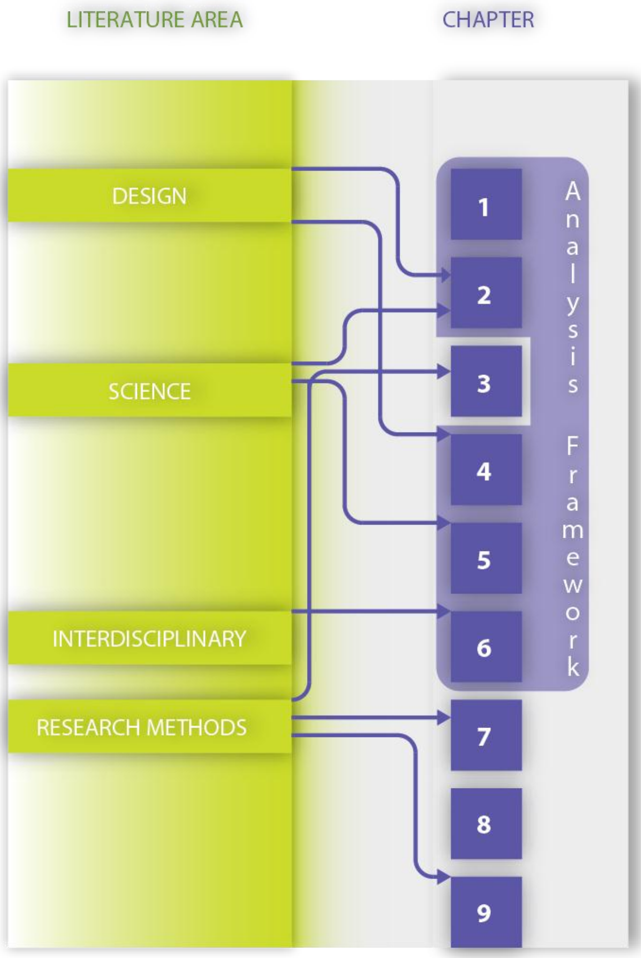

Diagram 3.3 Different areas of the literature review contributed to specific chapters of the analysis framework. (Research methods literature also contributed to the development of Chapters 3, 7 and 9)

The analytical framework provides the theoretical background for the research on relevant key themes. In this thesis, some individual chapters relate to each one of these themes. Chapter 1 explains how designers and scientists collaborate, and Chapter 3 illustrates the disciplinary differences between designers and scientists. Chapter 4 offers details on how designers work and Chapter 5 on how scientists work. In addition, Chapter 6 explains relevant theoretical elements from interdisciplinary studies.

3.4.2 Phase 3 Case studies

The case studies involved collaboration between a team of designers and scientists conducting research across a range of natural and applied sciences: medicine, biochemistry, engineering, material sciences, chemical engineering and plant sciences, genetics and chemistry.[7]

Also, officers from the University technology transfer office (UTTO) were involved at the beginning, liaising between the designers and the scientists, and during the case studies partaking occasionally in meetings as participant observers. The working group composed of designers, scientists and UTTO officers is called the Project team. The working group made up of designers is called the Design team.

- Project Team= (Scientist(s) + design team ± University technology transfer officer(s))

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[7] The choice of case studies from the Natural and Applied sciences over social and formal sciences responded to the natural and applied sciences direct linkage to technological development. This falls in line with the project "Design in Science"'s purpose to *"understand the impact of design skills on the development of new technology in the science base"* (Moultrie [2009]). It also followed a logistic reasoning: within the time and resources available for the research, the research team felt that including social sciences and formal sciences would have made the project scope too wide and unmanageable.

- Design team= (2 Designers (Industrial and Product) + project director)[8].

Occasionally, brainstorm sessions were carried out. Participants in these sessions varied but normally they included the project team plus guest designers and/or scientists.

3.4.2.1 Case study stages

There were two stages of case studies. The first stage included 3 *exploratory case studies* and the second comprised 2 *development case studies*. While the exploratory cases dealt with scientific research in various stages, the development case studies were concerned with scientific research in its early stages.

The case studies stages were defined by their purpose and length. The overall purpose of the case studies in the first stage was to enable an initial analysis of the potential impact of design expertise and to help focus the research objectives. The case studies were chosen to reflect a range of scientific research projects at different stages of development. This in turn would inform the selection of further detailed cases. The purpose of the

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[8] Since the case studies were conducted by participant observation, the design team was also the research team. This and further chapters will refer either to the research team or the design team according to the role they are performing.

case studies in the second stage was to examine the potential contribution of designers to scientific research at specifically its early stages[9].

Another difference between the 2 stages was of operational order: in the first stage the research team felt it was easier to get the interest of scientists that were already looking for a designer contribution to their pursuit of commercialising their research. In contrast, during the second stage the research team felt more confident to approach scientists with no commercial intentions, because they already had the results of their first stage case studies to show their capabilities and the collaboration's potential benefits to the scientists.

3.4.2.2 Case study duration

The initial idea was to undertake 4 exploratory case studies of 2 months of duration each over a period of 8 months for the first stage, and 5 development case studies of the same length over a period of 20 months for the second stage. However, this plan was modified due to a number of factors.

First, timetabling meetings between designers, busy scientists and officers from the UTTO with different work schedules and

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[9] The initial case studies plan was outlined in the "Design in Science: Deign Disruption" document by James Moultrie[2009)

working in different locations was not always easy. Secondly, the type of design projects undertaken during the case studies and their complexity required longer periods of development than expected. In fact, some of the projects offered the designers new challenges they were not used to, such as dealing with very small objects or developing and prototyping concepts using solely design software. Also, the tight correlation between understanding the underlying scientific principles of the projects and their success demanded additional sessions of consultation between designers and scientists to ensure that these principles were correctly understood. Furthermore, in some of the projects the design need or the project scope was (deliberately) not clearly identified at the outset, which also resulted in additional consultation and discussions. Thirdly, the designers were working in a context in which access to modelling and prototyping facilities and equipment was limited. Having to resort to external providers for the development of prototypes and being limited by cost, the design development sometimes took longer than would have been the case if these resources had been more readily available. The end result was that the length of the case studies in the first stage was 4, 8 and 9 months over a period of 12 months (some of the cases overlapped).

At the end of the first stage the design group felt that trying to limit the duration of the case studies to 2 months was not beneficial. The results suggested that in order to obtain a more meaningful contribution to scientific research, the development cases studies of the second stage needed to be longer and to have more flexible termination deadlines. So instead of aiming to complete the 8 case studies originally planned, the group decided to undertake fewer cases and spend as much time as necessary to complete them. Eventually 2 of these cases evolved and developed, becoming longer projects of 15 and 20 months and were the main development case studies.

3.4.2.3 Case study selection

The process of selecting case studies changed during the project. At the beginning of the study it was easier to choose from a variety of potential case studies, since the design team was looking for scientific research projects at different stages of evolution. However, towards the second stage the choices were less abundant and the available case studies were less suitable, since similar case studies had already been carried out in the first stage. Thus it was more difficult to find case studies with the potential to generate new knowledge.

The search for case studies was carried out using three different approaches. First, the university's research service division was approach by the research team, to obtain names of scientists to conduct initial interviews. They acquired a long list of potential scientists for collaboration. The research team contacted 40 of them and eventually interviewed 12 scientists. These scientists were asked to name others with a potential interest in participating in the case studies. This approach resulted in the identification of one of the development case studies. The second strategy was to spread word about the research by making presentations in events linking research and entrepreneurship in the university. This also involved conversations with departmental entrepreneurship champions. From this came one of the main development case studies. The third strategy was to contact the University Technology Transfer Office (UTTO), looking for potential interested scientists. The research group hoped that the UTTO's university-wide network of scientists would be helpful in making contact with scientists interested in developing their research towards a commercial venture. This proved to be the most effective method to find case studies. The UTTO did more than simply provide names, actively seeking out potential case studies, facilitating meetings with the scientists and supporting and following the case studies which they helped to obtain. Five of the case studies came from the UTTO. A detailed account of the case studies will form the content of Chapter 7 of this thesis.

3.4.3 Phase 3 Collaboration matrix/findings generation (Data Analysis)

The data from the case studies were analysed to determine patterns, common issues and differences among them. Analysis was carried out mainly through the narrative reconstruction of the study cases, using recordings, documents and design outputs to trigger memories and reflections. Graphics, tables and diagrams were also fundamental in supporting analytical work.

The data analysis was developed through different activities, starting almost simultaneously with the case studies and extending over the synthesis stage. During the case studies several analytical activities were regularly completed:

- After meetings and work sessions between designers and scientists, the designers reverted to their role of researchers to recap and reflect on the events on the day. This practice helped to identify meaningful aspects of the interaction between designers and researchers, and to improve understanding of the collaboration.

- A written diary was kept with reflections and thoughts on the development of the case studies. This contributed to keep important memories of the collaboration, but also to analyse different aspects of the collaboration.

- Academic papers, conference presentations and a first year report carried out during the case studies stage helped to develop an initial analytical work, consisting of making an overall comparison between the preliminary case studies results and data from literature.

During the analysis stage three main analytical activities were carried out. First, a collaboration matrix was developed and case studies were mapped onto it. Next, each of the case studies was examined to determine the stage of scientific research in which they were positioned. Finally, the case studies were scrutinised against each of the research sub-questions utilising the collaboration matrix, the case studies descriptive account, and varied aspects of the analytical framework.

The collaboration matrix was developed with the purpose of mapping collaborations to visualise how design activity and scientific research occurred, and the involvement of designers and scientists. The development of the matrix aimed to make it possible to look at the internal aspects of each case study and to draw comparisons between them.

The collaboration matrix's main structure was based on Mackay and Fayard [1977]'s model of representation for projects involving design and scientific activity. The collaboration matrix aspects relating to scientific research were based on relevant literature about the scientific research process (explained in Chapter 5 of this thesis). Aspects related to design were based on the individual researchers' design experience but also on observations about the way in which the design work occurred during the case studies.

After this, each of the case studies was mapped on the collaboration matrix (illustrated in Chapter 7). For that purpose, the research team met to recall and annotate collaboration development and events. Email exchange between designers and scientists was also reviewed, as were the notes in the researcher's diary.

In order to reinforce the validity of the tool and the researchers' recollection/description/mapping of the case studies, scientists involved in the case studies were interviewed. The interviews elicited their views on the accuracy of the collaboration matrix with regard to its description of scientific research activity, and in respect of the reliability of the researchers' account of the collaboration. After this the matrix structure and some aspects of the mapping were modified accordingly.

Finally, the matrix collaboration served to analyse the case studies in respect to the research question. This involved a twofold strategy. On one hand, the matrix was utilised as a tool to examine specific aspects of collaboration within the case studies. This was done with the purpose of understanding the different ways in which designers and scientists can collaborate. On the other, it was employed to make a comparison between evidence obtained from the case studies and existing knowledge about the designers' contribution to scientific research.

In order to analyse the case studies with regard to the stage of scientific research in which they were positioned, this research examined the case studies retrospective account, and located the case studies on the diagram of scientific research (developed in Chapter 3). The analysis included a reflection on the impact that design intervention had on the research direction in each of the case studies.

This research scrutinised all case studies differently according to the research questions. To start with the question about the possible forms of collaboration between designers and scientists, this research examined different aspects of collaboration evidenced in the collaboration matrix case studies maps. Then, the results were compared with the model of collaboration developed in the analysis framework (see Chapter 6).

To address the questions about the role of designers in scientific research, their contribution to scientific research and the barriers and enablers of collaboration, this research drew conclusions from the retrospective account of the case studies and compared them with specific and relevant aspects from the analysis framework (Chapters 1, 4 and 6).

To examine the question on the areas of scientific research on which design can have an impact, this research compared the conclusions previously drawn from designers' roles and contribution with a model of the scientific research process based on the collaboration matrix (see further information in Chapter 7).

3.4.4 Phase 4 Report writing (Data Synthesis)

The data synthesis of this research was developed through the writing of this thesis. Starting with the development of the analysis framework, each of its main themes was assigned to a chapter. At the beginning of each chapter there is an introduction, followed by the respective theme development and a concluding summary, normally illustrated by graphics or tables.

The case studies were synthesised through a narrative description and by their mapping on the collaboration matrix. There is a general introduction which describes how the case studies were conducted, followed by an individual description of each of them. Pictures complement the case studies description.

Most of the findings of this research are explained with reference to the individual case studies. Accompanied by graphics, tables, diagrams and pictures, the findings are structured in sections corresponding to each of the individual research sub-questions.

At the end of this thesis, conclusions are made with written explanations and diagrams.

3.5 Summary and implications

This chapter explains important aspects of this research approach and methodology. It describes how the approach subscribes to the qualitative research paradigm, and how its philosophical approach is founded on a constructivist world view. The chapter also explains why case study has been chosen over other potential research approaches, and that the main method of collecting data is participant observation. The chapter ends by presenting how the research was conducted, explaining its main phases.

Some aspects related to the research approach and methodology of this research will be further developed in other chapters. This has been done consciously, so as to improve the flow of the argument and to make the reading of this thesis easier.

For example, further explanation of the way in which the case studies were conducted will be found in Chapter 7, to introduce the case studies and to set the context for them. To similar effect, details of the development and application of the collaboration matrix has also been included in Chapter 7. Similarly, methodological explanations on how the data was analysed are included in Chapter 8, to reinforce the validity of the analysis and findings. Finally, an analysis of the limitations and scope of this research with regard to its methodological stand is located in the conclusion section, so as to make possible direct references to the work conducted during the research and explained in this thesis.

The following three chapters constitute the main core of the analysis framework of this study. By explaining the nature of design work (Chapter 4) and of scientific research (Chapter 5), and by illustrating relevant aspects of interdisciplinarity, these chapters provide elements of reference and comparison for the analysis of the case studies and the conclusions made in Chapter 8 and 9.

4. THE NATURE OF DESIGN WORK

As a result of this, Chapter 4 explores more in-depth the nature of the design activity, explaining what designers are capable of doing and how they normally engage in collaboration. The chapter explains that the nature of the designer's work is fundamentally creative, and argues that designers' activity is about ideating new purposeful and feasible entities, according to the circumstances in which they are or will be made and utilised, and geared towards the needs of users and producers. It also clarifies how the project and the design process are essential components of design activity, and outlines design as a very complex activity that requires designers to have a wide range of competencies. The chapter describes these competencies, deconstructing them in their main traits: Knowledge, Skills and Behaviours.

The chapter also explores the types of collaborative engagements in which designers are normally involved. The chapter suggests that designers can engage in collaboration according to the function they have in working groups, to the point they enter in the collaboration, and on the level of involvement in defining a problem and the initial solution design concept.

This chapter concludes with two tables which will later be contrasted with evidence from the case studies. Table 4.1 summarises the capabilities of designers and Table 4.2 presents different modes of design engagement.

4.1 What is design?

In order to explain what a designer is able to do it is important to define what design means in the context of this study. It would be useful to draw on a standard definition of design but this may be problematic since it is apparent that there is no consensus amongst scholars and practitioners (Friedman [2000]). Diversity in professional design practice and continuing change and expansion in design "meaning and connections" make it difficult for the design community to agree on a definition (Buchanan [1992]).

However, there have been attempts by professional design associations to outline standard design definitions that can be useful for the purpose of providing a framework to map designers' skills. For example, the International Council of Societies of Industrial Designers defines design as "*a creative activity whose aim is to establish the multi-faceted qualities of objects, processes, services and their systems in whole life cycles*" (ICSID [2011]). ICSID also states that design seeks to "*discover and assess structural, organizational, functional, expressive and economic relationships*" and describes design as "*an activity involving a wide spectrum of professions in which products, services, graphics, interiors and architecture all take part. Together, these activities should further enhance - in a choral way with other related professions - the value of life.*" In Britain the Chief Design Officer of the Design Council explains how they adopted the definition outlined by Sir George Cox in the Cox Review (Mat [2011]). He states, "*'Design' is what links creativity and innovation. It shapes ideas to become practical and attractive propositions for users or customers. Design may be described as creativity* *deployed to a specific end"* (Cox [2011]. In the United States the Industrial Design Society of America (IDSA) defines design as *"the professional service of creating and developing concepts and specifications that optimize the function, value and appearance of products and systems for the mutual benefit of both user and manufacturer*" (IDSA [2011]).

As illustrated in Diagram 4.1 these definitions suggest that designers' activity is about ideating new feasible entities (namely objects, processes, services, systems, etc). Also, that those entities are meant to fulfil a purpose in the best possible way. In addition, they need to be designed according to the circumstances or context in which they are or will be made and utilised. Lastly, design is geared towards the needs of users, producers and other stakeholders.

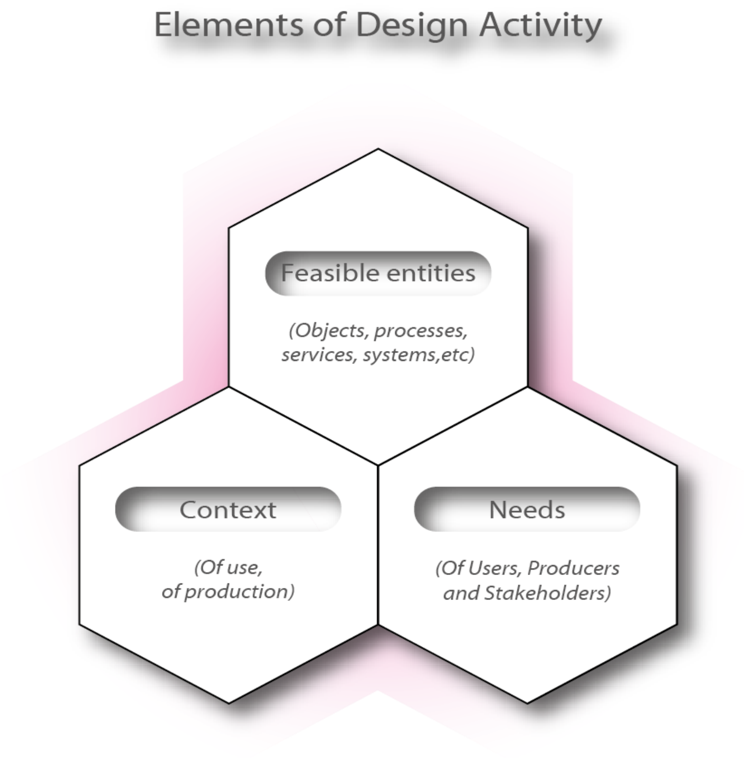

Diagram 4.1 *Elements of Design Activity*

However, these definitions of design seem to give little attention to two other fundamental aspects of design activity. First is the “design project”, which is the unit of work of designers. Design tasks or commissions are often taken by designers as a project, hence the project becomes the context in which designers and clients interact. As Lawson & Dorst explain *“…designers and design researchers alike tend to focus almost exclusively on optimising design performance within the context of the concrete design project*” (Lawson & Dorst [2009] p. 62). Second is the design process, which is the way in which designers carry on with their design activity. The design process refers to a series of purposeful design activities/steps carried out over a period of time in order to complete a design task. Bernhard Burdek explains that the design process is the “creative” process employed by designers and that “*each design object is the result of a development process influenced by various – not only artistic – conditions and decisions*” (Burdek [2005] p. 225). Hugh Dubberly, in his compendium of design process models, explains the importance of the design process by saying, *“Our processes determine the quality of our products. If we wish to improve our products, we must improve our processes; we must continually redesign not just our products but also the way we design. That’s why we study the design process. To know what we do and how we do it, to understand it and improve it, to become better designers”* (Dubberly [2004]). The design process is a fundamental part of design and of many of the designer’s capabilities that are associated with it. This has several implications:

- First, designers require the development of a special “design” mindset and attitude to help them in dealing with their main concern, which is principally what ought to exist: design is about creation.
- Secondly, since designers work with design output of varied nature either tangible and/or intangible, they need to develop appropriated cognitive abilities.
- Thirdly, designers need to develop prospective and experimental abilities since their ideation process needs to be guided by considerations of viability (since the entities it creates need to be feasible), and by thoughts about functionality (since there is a purpose for the entity to fulfil).
- Fourthly, designers need to develop project related skills and to become competent in the design process.
- Finally, design activity requires a good understanding of reality and contextual considerations. For this, designers ought to have a good basic knowledge of a wide range of human activity, and need to be able to acquire useful knowledge of various kinds in short periods of time.

In conclusion, design is a complex activity which requires designers to develop certain abilities, attitudes and knowledge. Designers need to gain design competence[10].

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[10] Wim Westera explains that complex situations require the development of skills: *“The concept of competence is strongly associated with the ability to master such complex situations—and it is assumed that ‘competence’ transcends the levels of knowledge and skills to explain how knowledge and skills are applied in an effective way”* (Westera [2001]).

4.2 Design competence

Design competence is the ability to use a particular set of knowledge, skills, behaviours and attitudes in response to a problem in a specific context, Westera [2001]; Baartman et al. [2011]. For this reason, a good description of designers' capabilities should include an explanation of all design competence traits: knowledge, skills and behaviours/attitudes[11]; knowledge referring to what an individual knows about and understands, skills meaning what an individual can do, and attitude/behaviour defined as the disposition of an individual to use knowledge and skills in a specific context/situation.

Even though authors have attempted to define design competence by making lists of competence traits, it seems that a unifying description of all of them has not been made. Even further, often authors do distinguish between them, making the characterisation of design competence difficult. For example, Conley [2004] (p. 46) identifies designer's core competencies as follows:

"1. The ability to understand the context or circumstances of a design problem and frame them in an insightful way
2. The ability to work at a level of abstraction appropriate to the situation at hand
3. The ability to model and visualize solutions even with imperfect information

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[11] Even though there are several interpretations of what competence is, it seems that authors agree to accept knowledge, skills and attitudes as the "integrated pieces" that form competence (Baartman et al. [2011]; Delamare Le Deist et al. [2005]; Ashworth et al. [1990]).

4. An approach to problem solving that involves the simultaneous creation and evaluation of multiple alternatives

5. The ability to add or maintain value as pieces are integrated into a whole

6. The ability to establish purposeful relationships among elements of a solution and between the solution and its context

7. The ability to use form to embody ideas and to communicate their value"

It is noticeable that some of these competencies refer to different and probably uneven combinations of knowledge, skill and/or attitudes. In competency point 3 for instance, modelling and visualising is a strong component as opposed to competency point 4 in which the emphasis seems to be on an attitude (opting for a particular approach to problem solving). It is also noticeable that the author does not make explicit any particular knowledge designers might need in order to be "competent".

Bernhard Burdek describes design competence differently, outlining a group of tasks which designers need to "fulfil", instead of directly making a definition of designer capabilities. He states that designers should:

- *"visualize technological progress*
- *simplify or make possible the use and operation of products (hardware or software)*
- *make transparent the connections between production, consumption and recycling*

- *promote and communicate services, but also – pursued energetically enough*
- *help to prevent products that are senseless”* (Burdek [2005] p. 16).

These tasks suggest that designers might need certain skills, e.g. visualising, simplifying processes, promotion and communication. Also, they imply that designers should have certain attitudes or behaviours, for example, they should “pursue energetically”. However, Burdek’s list seems to be too generic, not comprehensive and does not make explicit any knowledge designers might need in order to design.

Rita Sue Siegel [2008] perhaps offers one of the most comprehensive lists of designers’ competencies. She proposes 3 main groups of designers’ core skills: Creative, Cognitive and Management Skills. She also offers a list of ideal designer personal attributes. Although extensive, Siegel’s list makes no distinction between knowledge, skills and behaviours. For example, in her list of Core Creative Skills some of its items are actual skills e.g. “Hand Sketching”, but others refer to the type of knowledge designers need to have: for instance, having a “repertoire of colours, materials, finishes”. Also, other items do not refer to knowledge or skill but to behaviours, e.g. “considers environmental sustainability”.

From a different angle, Cross [1998] explains several competencies and attitudes which designers need according to his notion of the characteristics of design. Cross argues that design is rhetorical; therefore, a designer needs to be able to build arguments. He says that design is exploratory, hence designers need to have an attitude of discovery and be ready to jump into the unknown, actively seeking for the not known. He also says that design is emergent, so designers need to be flexible and adaptive; and that it is both opportunistic and abductive, so designers should be able to abduct.· Cross also states that design is reflective, therefore designers need to be able to reflect and to utilise tools that facilitate reflection e.g. sketching.[12] The author also propose that design is ambiguous, so designers need to be able to be divergent and convergent; and that design is risky, so designers need to be willing to take risks and able to commit in the presence of uncertainty.

It seems that for Cross, the nature of design activity is such that it is just as important for designers to develop tools as it is to develop an attitude and disposition towards the way they deal with issues. Cross seems to characterise designers by their competencies and attitudes but, like other authors, does not put much emphasis on the knowledge that designers may need to perform adequately.

It is apparent that authors prefer to emphasise skills and attitudes in describing designer competence, and not to put too much emphasis on knowledge. However, a taxonomy of design domains knowledge developed by

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[12] Cross [1998] identifies sketching as a tool for reflection, which enables designers to "*handle different levels of abstraction simultaneously*". Sketches "*enable identification and recall of relevant knowledge…assist problem structuring through solution attempts…* and*…promote the recognition of emergent features and properties…*"

Ken Friedman [2000] provides an extensive list of things that designers ought to know. Friedman establishes four main domains:

- Domain 1 Skills for learning and leading
- Domain 2 The Human World: the human being, the company, the society, the world and theory basics
- Domain 3 The Artefact: product development, design and manufacturing
- Domain 4 The Environment: natural environment, built environment, architecture, interior and installation.

Friedman argues that designers need to develop skills, knowledge and awareness in all these areas, but he does not explain the nature of such skills and does not give any details about which areas need to be well known or of which designers should be aware.

From a different perspective, Eckert et al. [2010], while examining "*the experience of being a designer and doing design*" in a series of workshops involving practitioners from a variety of design disciplines, identify several common aspects related to the design process and the project such as the role of materials and tools in design activity, the design practitioner's relationship with users and customers, and the use of representations as communication tools. These aspects serve to highlight the importance of the design process and the project in design practice, and reveal how knowledge of the design process is a fundamental part of design competence. In order to build a complete description of designer capabilities, a table has been included which summarises the competencies of designers (Table 4.1). Competencies have been split according to the generally accepted traits: knowledge, skills and attitude/behaviour. This table will be used as a reference for understanding what competencies are relevant for collaboration with scientists, and to examine if there are other competencies that have not been made explicit or identified which are also relevant. The table will also help to compare designers' competencies with those of scientists, to determine how they affect collaboration between them.

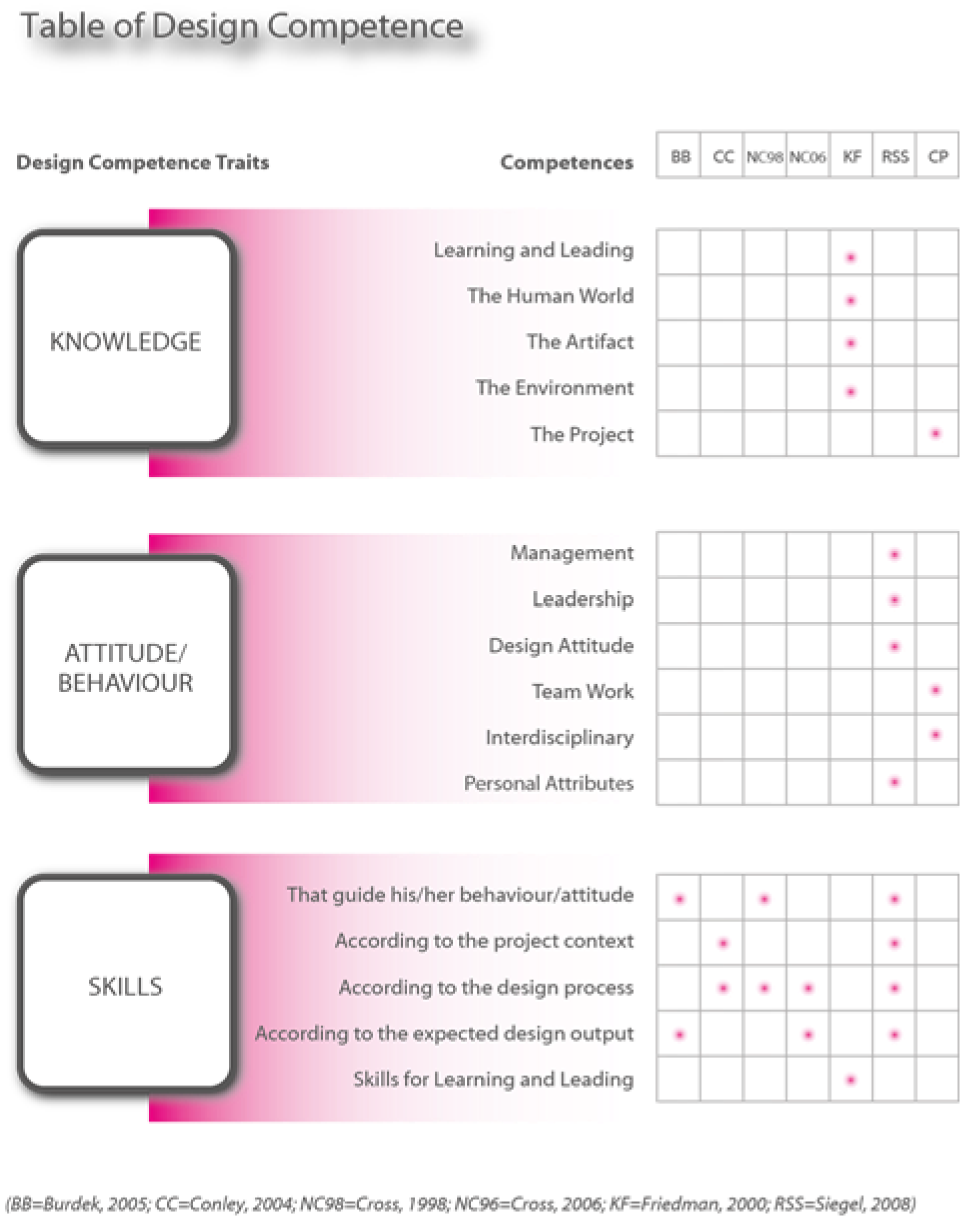

Table of Design Competence

Design Competence Traits	Competences	BB	CC	NC98	NC06	KF	RSS	CP
KNOWLEDGE	Learning and Leading					●		
	The Human World					●		
	The Artifact					●		
	The Environment					●		
	The Project							●
ATTITUDE/ BEHAVIOUR	Management						●	
	Leadership						●	
	Design Attitude						●	
	Team Work							●
	Interdisciplinary							●
	Personal Attributes						●	
SKILLS	That guide his/her behaviour/attitude	●		●			●	
	According to the project context		●				●	
	According to the design process		●	●	●		●	
	According to the expected design output	●			●		●	
	Skills for Learning and Leading					●		

(BB=Burdek, 2005; CC=Conley, 2004; NC98=Cross, 1998; NC96=Cross, 2006; KF=Friedman, 2000; RSS=Siegel, 2008)

Table 4.1 *Table of Design Competence*

4.3 Designers' different ways of working (designers' engagement)

Tim Parsons says that a designer can be either an employee or be commissioned by someone (acting as an independent designer), or can work speculatively without a client Parsons [2009]. This type of design engagement classification derives from the contractual terms of collaboration between designers and “clients”, and it might not be the best way to understand collaboration between designers and scientists in the context of scientific research. The rules of engagement between these professionals in this particular context are suspected of depending upon other values than commercial or contractual ones. However, this standard classification might be useful to highlight an important feature of designers’ engagement regarding the project ownership and initiation. When engaged as an employee or as a commissioned designer, the designer follows the project “initiated” by the employer/client, whereas as a speculative designer it is he or she who makes the project happen. This is a distinction that potentially affects the designers’ ownership of and commitment to the project, and it may also affect collaboration with scientists.

An alternative classification for designers’ engagement can be outlined by the specific role a designer may play in collaboration. As their role changes, the dynamics of interaction between designers and their working groups may change as well, and this can determine the type of design engagement. This can be seen in Howard & Melles identification of the different roles that designers can have in the context of “complex design projects” (Howard & Melles [2011]). The authors propose a list of roles defined by the function designers can have in a working team. These roles were identified from a case study that involved collaboration between designers and a multidisciplinary team performing a design task.

The first role these authors identify is "*Design lead*", in which the designer assumes the role of activities guidance and conversation facilitator. Howard et al. notice that in this role, designers move "*out of the traditional solo design expert role and into being a design subject matter expert leading a multidisciplinary team*" (Howard & Melles [2011] p. 154). The second role is "*Teacher*", in which designers help team members to improve their design thinking capabilities through the design process. The authors stress that "*design thinking is partly an education process"* that is *"best learned through doing rather than explaining*", implying perhaps that non-designer team members learn from designers as they interact with them. Another role designers can play is "*Facilitator*", in which designers create an adequate environment to make possible team members to work efficiently and comfortably. Howard et al. underline that *"facilitation relies heavily on empathy, active listening, and mindfulness*." The last role identified by Howard et al. is the "*Director*". In this role, the designer orchestrates the design experience, bringing together the team and integrating aspects of the other 3 roles.

Other options for identifying design engagement can be drawn from Paton and Dorst's paper describing designers' perceptions of the designer's role in design briefings Paton & Dorst [2011]. The authors examine the involvement that designers and their clients have in the definition and formulation of the "*problem space*" and the "*solution space*". While the "problem space" refers to identification of the problem designers are meant to solve, the "solution space" refers to the primary design concept solution; in other words, the initial design hypothesis Liedtka [2004]. Paton et al. also look at the designer's point of entry in the design project as illustrated in Diagram 4.2.

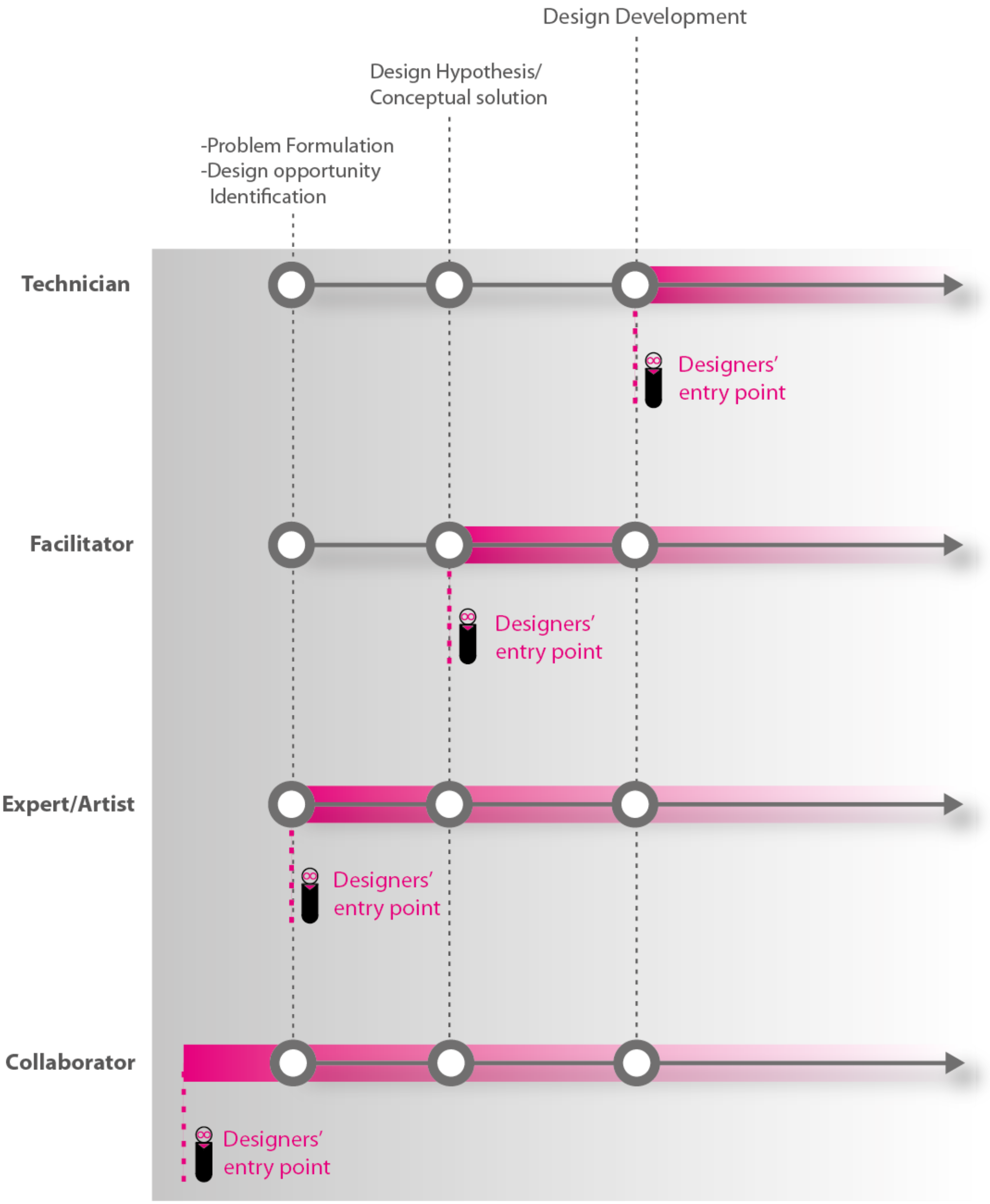

Diagram 4.2 *Author's visualisation of Paton & Dorst's notion of designer roles*

According to Paton the main roles identified are:

- Technician: the client knows what is needed and has a clear idea of what is required to address it. The designer executes the project according to the client's idea. The designer is brought to the project after it has been formulated.
- Facilitator: the client knows what is needed but does not know how to address it. The designer advises on how to achieve this, and then continues with the project. The designer is brought to the project near the end of its formulation.
- Expert/Artist: the client has a partial idea of what is needed. The designer is called to help identify the need and to devise ways to address it. After this, the designer develops the project. The designer is brought to the project in the middle of its formulation.
- Collaborator: the client and the designer both work on identifying the need and devising ways to address it. The designer then continues with the project.

Paton et al. emphasise the designers' preference for being involved early in the formulation of the project and being able to define with the client both the formulation of the problem and the conceptual solution. Their favourite roles are Expert/Artist and Collaborator, especially when they consider that the client's framing of project is "*unworkable, ill-suited or unnecessarily limiting*."

Table 4.3 shows the different ways in which designers engage in collaboration, summarising the approaches explained in this chapter.

The table outlines a list of aspects that determine the type of design engagement (determinants). It also includes different correspondent ways in which collaboration changes (modes of engagement). This table will be used to understand what types of engagement are present in collaboration between designers and scientists. It will also be utilised to explain how collaboration can be affected by the way in which designers are engaged and to identify potential idiosyncratic new types of design engagement in scientific research.

Table of Design Engagement models

	Determinants	Mode of engagement*			
I	Parsons (2009) Initiator	Client	Designer/client	Designer	-
II	Howard & Melles (2011) Role	Lead	Teacher	Facilitator	Director
III	Paton & Dorst Model (2011) Designer's Entry Point/ involvement	Tecnician	Facilitator	Expert/Artist	Collaborator

** There is no vertical correspondance between the models*

Table 4.2 *Table of Design engagement models*

4.4 Summary and implications

This chapter describes the main elements of design practice, showing its creative character and highlighting the designers' need to have users and context as the centre of their activity. Also, it suggests that the design project is the fundamental element of interaction between designers and clients/users, and that the design process is at the centre of designers' activity.

The chapter also illustrates how design is a complex activity that requires from design practitioners an ample range of knowledge, skills and behaviours/attitudes. It presents a map of Design Competence, integrating different but apparently incomplete existing models. This map will be used as a point of reference to identify those design competence traits that influence collaboration between designers and scientists, and to understand how they complement or contrast with those of scientists, while working together in the context of scientific research.

In its last part this chapter attempts to outline the way in which designers engage in collaboration. It presents three different angles. The first one makes reference to commercial-contractual modes of engagement. The second refers to the roles that designers may play in collaborative effort in interdisciplinary groups. The third one looks at the level of influence of the designer in the initial conception of the project, and in his/her point of entry to the project. This part concludes by proposing a Design Engagement table that integrates these three views. This table will serve, together with other models of interdisciplinary collaboration explained later on this thesis, to understand the collaboration process between designers and scientists, and to identify if there are emerging forms of design engagement in the context of scientific collaboration.

The next chapter will continue by developing understanding of the nature of scientific research. In its first part, the chapter will offer an overview of the two dimensions of scientific research, the rational and the social. In its last part it will describe the types and focus of scientific activity, emphasising the similarities and commonalities of basic and applied research, and explaining its relationship with technological development.

5. THE NATURE OF SCIENTIFIC RESEARCH

Chapter 4 described design activity, revealing its creative character and the importance of the user and the context as well as the project and the design process. The chapter also grouped design competence according to its main traits: knowledge, skills and behaviours/attitudes. It also outlined the way in which designers engage in collaboration from three different angles: engagement defined by the type of contract, or by the roles designers play in working teams, or by their influence on the definition of the project and their point of entry in the project. This sets a point of reference to help understand the role of designers in collaboration with scientists within scientific research.

Chapter 5 outlines scientific research, arguing that its traditional linear model does not reflect its day to day practice. Instead, scientific research activity is geared towards discovery on the one hand and towards credibility on the other. These two directions determine the main dimensions that encompass scientists' activities: the rational and the social. The chapter also presents a discussion of the types and focus of scientific research. It suggests that scientific research can be basic and applied, and that there are strong links between it and technological development. The chapter explains that while scientific research and technology can be disassociated and not necessarily be co-dependent, they still can contribute to their mutual improvement. This chapter concludes by presenting a model of scientific research in relation to application development, which connects basic and applied research. This model will be used to help explain, differentiate, and map the role and contribution of designers in the different stages of scientific research based on findings from the case studies. It will also be employed to identify the areas of scientific research in which designers can contribute.

Since this study intends to examine collaboration between designers and scientists in the context of scientific research, it is important to look at scientific research and at relevant issues regarding the practice of science. Of special interest is the discussion concerning the debate of pure and applied science, and the relationship between science and technology.

Scientific research is strongly associated with the practice of the scientific method. This suggests that scientific research is a rational, standardised and controlled process, and also that scientific research practice should be similar across all scientific disciplines, independent of scientists' particular traits. Literature on the practice of science informs that this is not the case, and portrays scientific research practice as a fluid process which varies across disciplines and researchers. This section explains the nature of this process.

Finally, scientific research has been traditionally divided in two categories, "applied" and "basic". Current literature on science suggests that this distinction has lost its relevance in current research practice, and links scientific research to technological development. This section explains how scientific research, applied or basic, relates to technology.

5.1 What is scientific research? The dimensions of scientific research

In general terms scientific research is the practice of conducting research using the scientific method in order to understand the world. Accordingly, the scientific method becomes the means by which scientists produce new scientific knowledge (Niiniluoto [1993]). In other words, scientific research is strongly associated with the use of the scientific method.

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*".

This definition of the scientific method suggests that scientific research is a linear and sequential process. Stokes [1997] (p. 6) cites Harvey Brooks, emphasizing 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*".

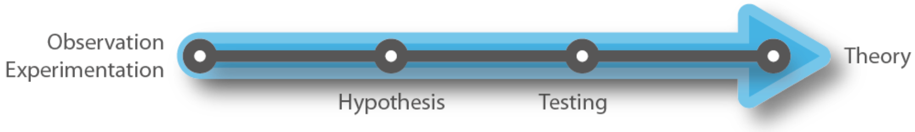

Diagram 5.1 *Representation of the linear model of scientific research*

However, it has been proposed that scientific research is not a linear process and that the realities of conducting scientific research are not entirely reflected in the traditional observation/experiment-hypothesis-testing-theory model of the scientific method. Grinnell [2009] introduces a model of scientific research based on what he calls the "everyday practice of science". In this model, Grinnell recognises the social character of scientific research, arguing that scientists engage in "*two conversations, one with the world to be studied, and the other with other members of the research community*."

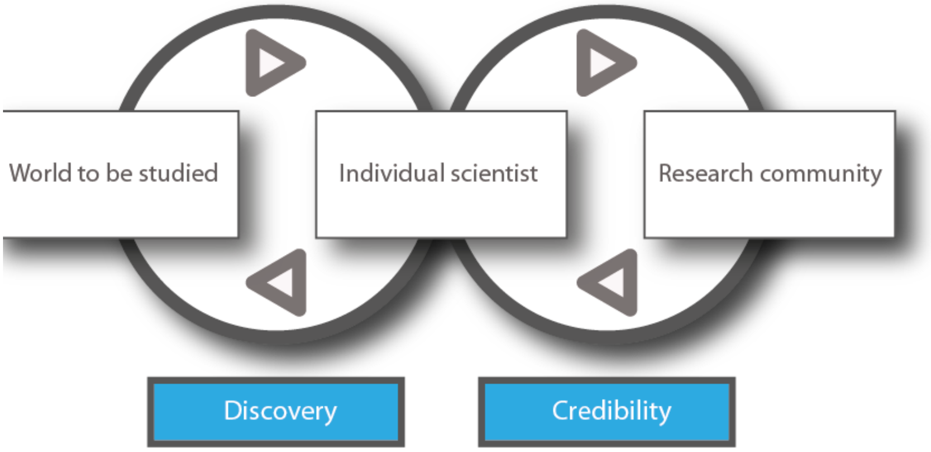

Diagram 5.2 *Everyday Practice of Science, based on Grinnell [2009] (p. 5)*

Grinnell's model suggests that the activities related to scientific research are on one hand concerned with the subject under study, and therefore of a rational and intellectual nature (or practical in some instances, for example when setting experiments). On the other they are also related to interaction with the scientific community and consequently of a social and communicative character.

Bauer [1992] also proposes that the traditional model of scientific method and the characteristics associated with being scientifically methodical ("*Empirical, pragmatic, open-minded, sceptical, and sensitive to possibilities of falsifying*" (p .20)) are not a true reflection of what happens in science.

Instead, Bauer argues that scientific research is conducted in as many forms as there are sciences, specialisations and sub-specialisations. He says, for example, that "*much theoretical speculation and argumentation over very few facts is commonplace in palaeontology or in astronomy but not in chemistry or in geology*" and that "*physicists look to crucial experiments to decide amongst theories at one fell swoop, whereas astronomers are used to waiting for long periods of time for the accumulation of data to bring an end to the speculation*". He claims that "*The differences amongst adepts of the various sciences go beyond matters of theory, method and vocabulary to subtler habits of thought and even to customs of behaviour*" (p. 25). Bauer also highlights that the way that scientific research is conducted in real life is strongly influenced by the ability, competence, dedication and honesty of the scientists that carry it out. He also explains that the stereotype of the cold and rational scientist is very far from reality and points out that the human condition of scientists prevents them from fitting the stereotypes.

As noted by Grinnell [2009], part of scientific research relates to the social interaction of scientists with the scientific community. This interaction occurs when scientists seek 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. This social aspect of scientific research has been explained by Grinnell [2009] (p. 64) with his "*credibility model in sciences*" and by Bauer [1992] (p. 45) with the "*knowledge filter model*". Grinnell's model is based on the interaction of scientists with both their own research group and with outsiders (editors, reviewers, research community, other scientists and the general public).

The model outlines three stages. The first is the "*Discovery claim"* stage, in which the researcher discusses and weighs up his ideas with his own research team/group using notebooks and manuscripts. The final outputs of this stage are manuscripts written in a style appropriate to the scientific academic community. The second stage, "*Credible discovery*", includes the evaluation of these papers by editors and publishers, in an iterative process that results in the publication (or rejection) of these papers. This stage includes the recognition of the validity or level of interest of the papers by being cited in the work of other members of the scientific community. The final stage, "*Textbook fact"*, includes the publication of work in books, confirming acceptance of the scientists' ideas by the wider scientific community and establishing interaction with other scientists and the general public.

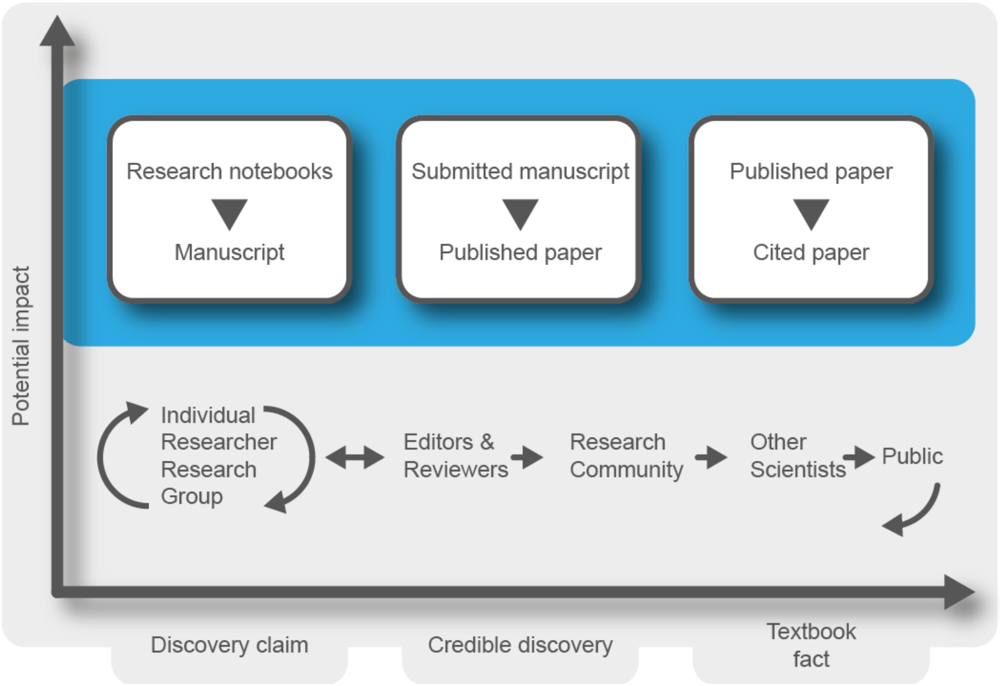

***Diagram 5.3** The Credibility process in science according to Grinnell [2009] (p.64)*

Bauer's model follows a similar sequence of events, but unifies the individual and social stages of scientific research. He reshapes the traditional linear scheme of scientific research and places it in a conical shape with stages that are connected through "*filters*". Research is carried out in a first stage called "*Frontier science*". Subsequent stages filter the research looking for bias, error, dishonesty, mistakes, un-interestingness, fraud, obsolescence and inadequacies.

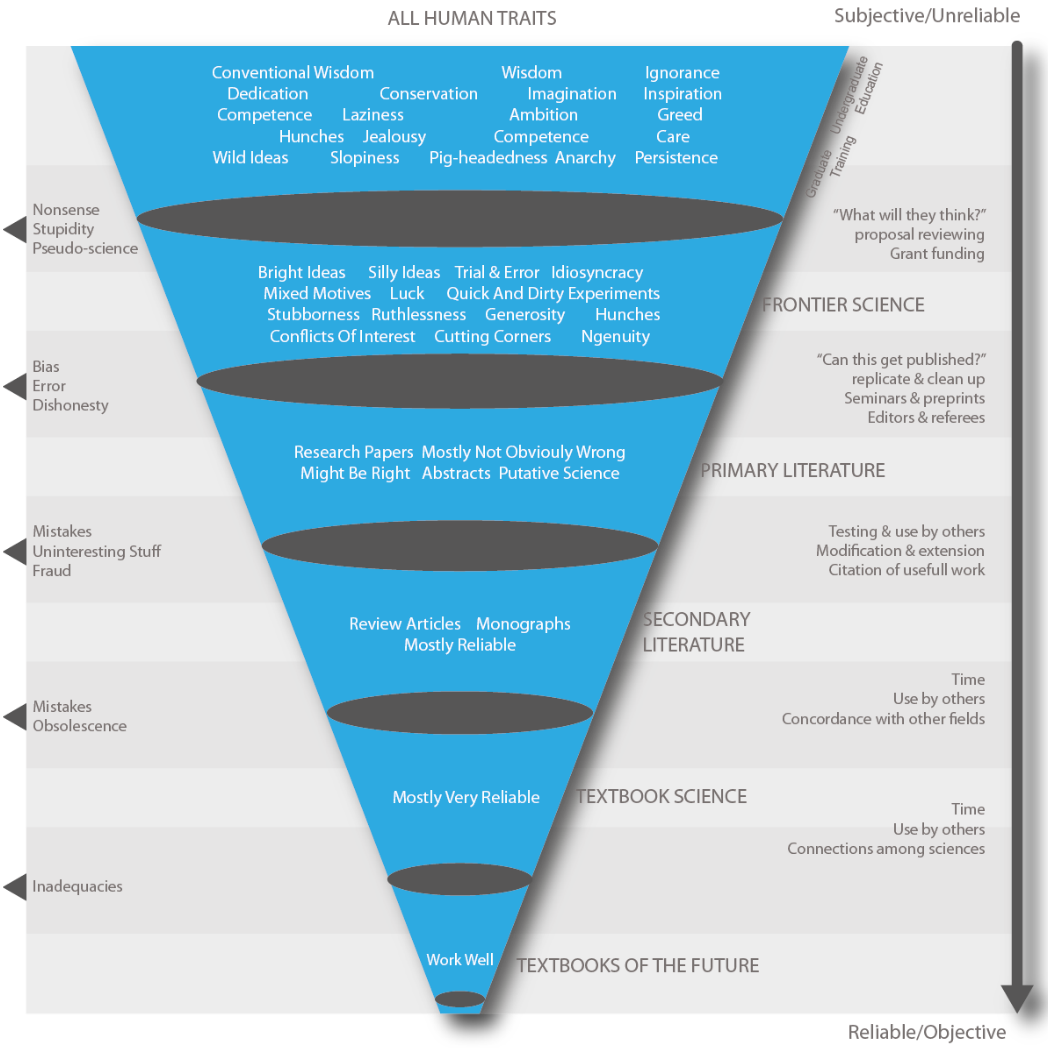

Diagram 5.4 *The Knowledge Filter, from Bauer [1992] (p.45)*

To summarise, the day to day practice of scientific research is a complex activity that varies according to the scientific discipline in which it takes place and to the personal characteristics of the scientists that practice it. However, there are two overarching but distinctive and interconnected dimensions in the practice of scientific research, the rational and the social (Diagram 5.5). The first dimension relates directly to 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. If identification of the dimensions of scientific research reflects its day to day practice, it does not reflect its purpose and drivers. The following section exposes this and reflects on the relationship of scientific research with technology.

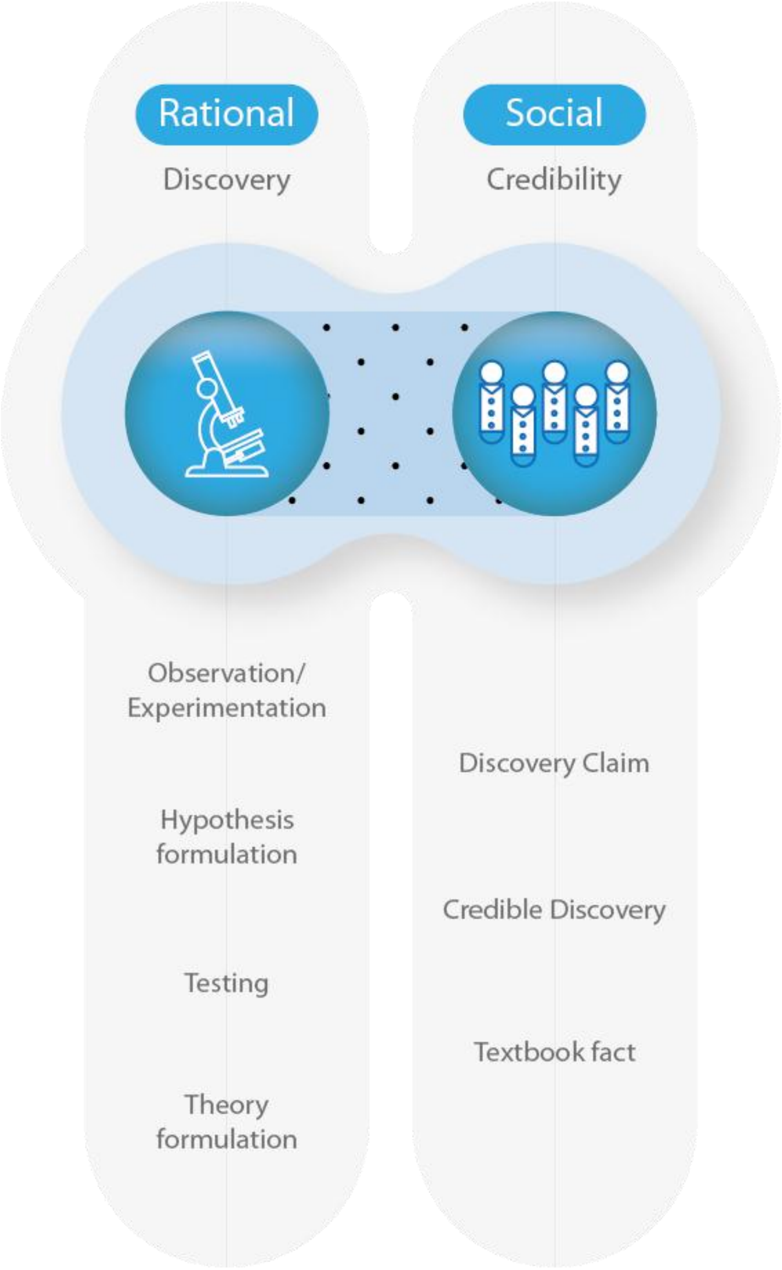

Diagram 5.5 *Two dimensions of scientific research*

5.2 Basic /applied scientific research

It is commonly accepted that scientific research can be classified into basic and applied. According to Pielke & 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.

However Pielke & Berly argue that "basic" science is a euphemism for "pure" research, which strips it from its 19th century connotation of "science for the sake of science". In this way, pure scientific research appears in the form of "basic" at the outset of "applied" science, which became acceptable to mid-20th century funding bodies and policy makers in the USA and worldwide.

Confirming this, the Organisation for Economic Co-operation and Development (OECD) has outlined a classification of scientific research that is widely accepted by the scientific community, especially amongst science and technology policy makers. This classification focuses on the different purposes scientific research might have. The OECD [2002] proposes three different types of activity linked to scientific research:

- Basic Research
- Applied research
- Experimental development

According to the OECD, *basic research* is "*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*" (p. 30). Basic research is conducted with no purpose other than understanding and is driven by curiosity. 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).

Conversely the other type of scientific research, *applied research* has also the same drivers as basic research, but it is aimed towards a "*specific practical objective*". In this type of research, researchers address their efforts towards identifying potential applications for basic research, or finding novel ways of achieving "*predetermined objectives*". In this type of research, 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 on the boundaries of scientific research, and may often be part of different contexts such as industrial or commercial activity.

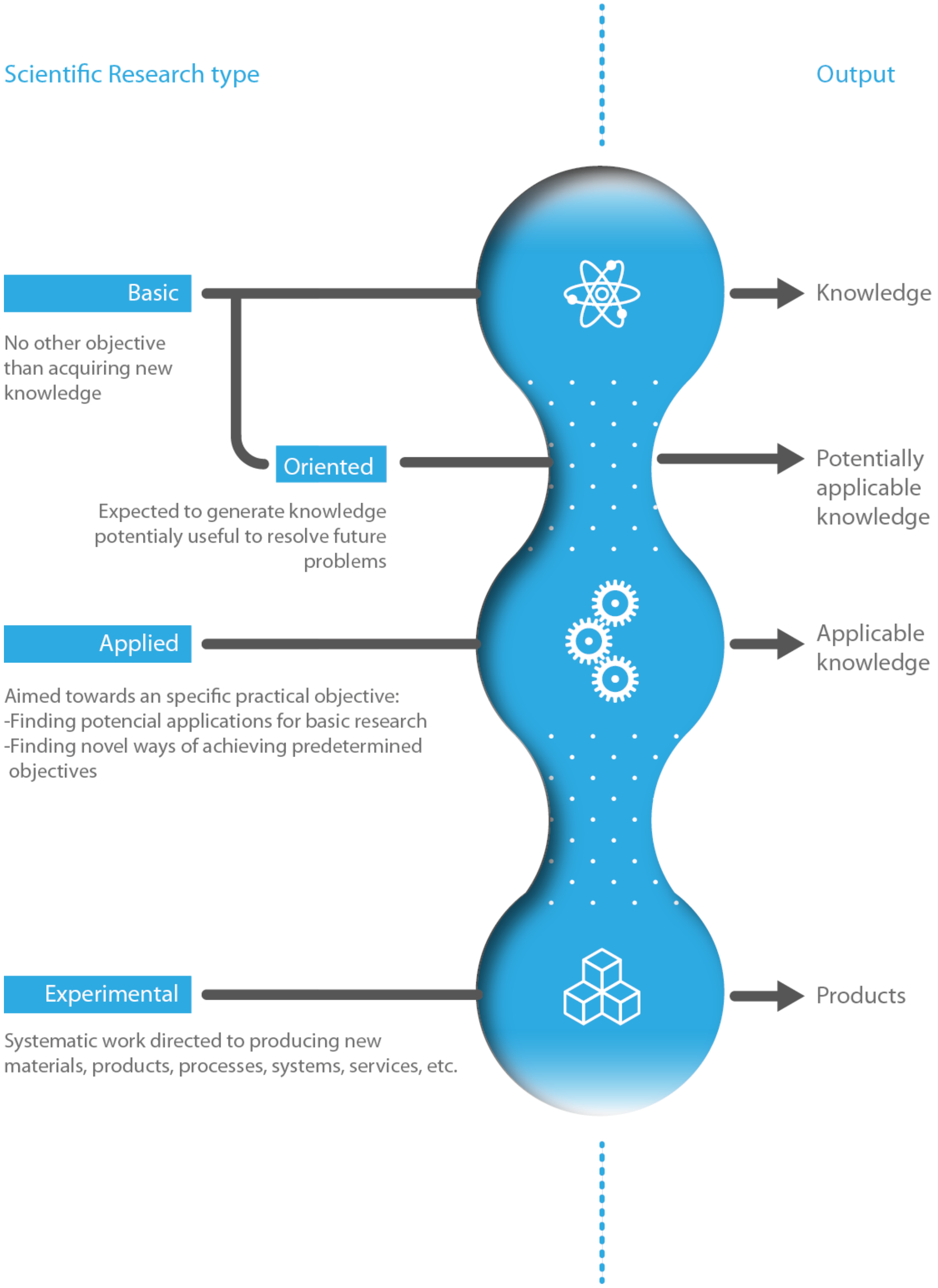

Diagram 5.6 *Interpretation of the OECD Scientific research classification by the author of this thesis*

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 both 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). This author also hints that current scientific research is more interested in the "*development of techniques rather than general theories, though the techniques (...) may have a general applicability*". In this way Webster's argument sets a strong link between scientific research and technology, associating science with industry and the development of techniques.

Close to Webster's thinking, a classification of scientific research by Niiniluoto [1993] introduces the concept of technology as an integral part of scientific research. This author utilises the concept of "*epistemic utilities*" referred to the "*research aims, progress and rationality of enquiry*" (p. 3) to explain the main difference between basic and applied research. Niiniluoto argues that the epistemic utility that characterises basic research is a combination of truth and information, in other words, "*truthlikeness*". Knowledge, which is the product generated from basic research, is validated by confirming its truthfulness. Conversely, the epistemic tool of technology is "*effectiveness*", alluding to the ability of "*material and social artefacts*", which are at the same time output and constituent of technology to fulfil the purpose for which they were created. Niiniluoto completes the classification by explaining that applied research sits somewhere between basic science and technology. He argues that applied science seeks to develop knowledge and to develop useful artefacts. For these reasons, applied research should also be evaluated by its "*correctness, informativeness and truthlikeness*", but also due to its potential impact in the world, by "*economic efficiency*" and "*ergonomical, ecological, aesthetic, ethical and social*" aspects. As seen in the previous chapter, these aspects are inherent to design and the use of these words in this context suggests that applied research may be linked to the practice of product design.

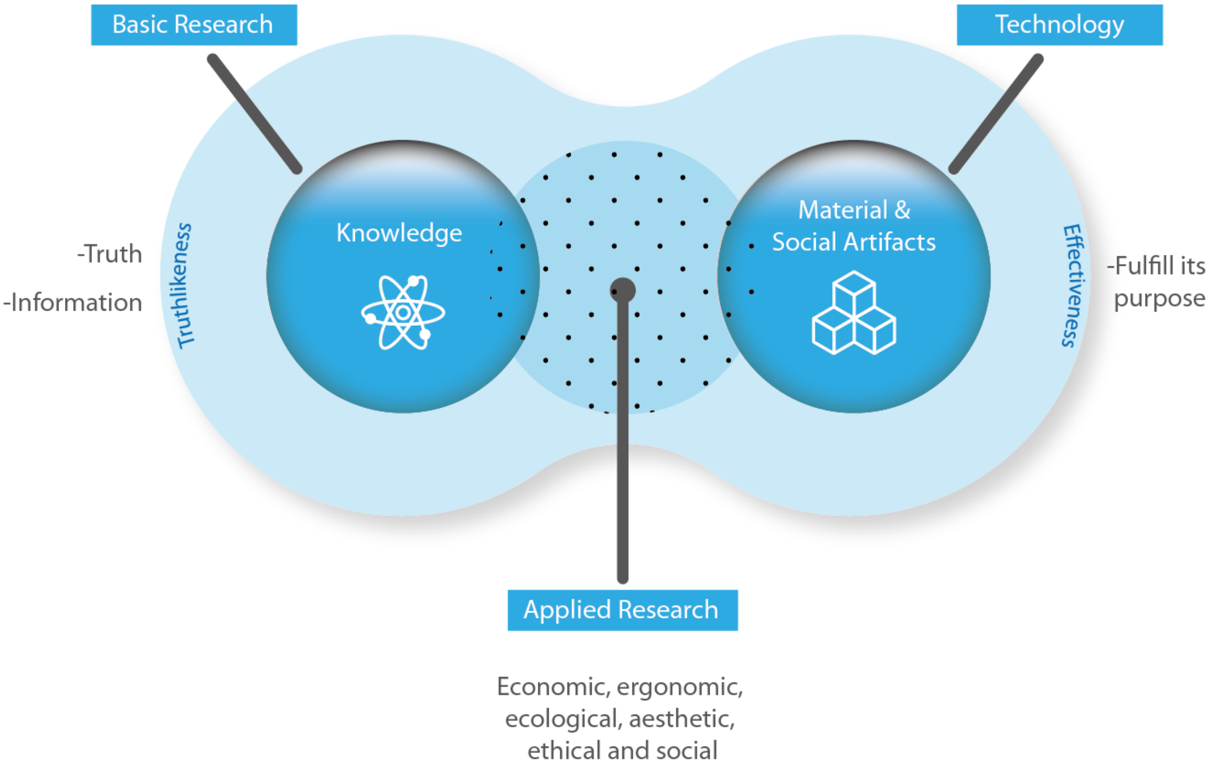

Diagram 5.7*Interpretation of Niiniluoto's classification of scientific research*

Niiniluoto's model seems to imply that the relationship between basic scientific research and technology is an important feature of scientific research. The following section explores this relationship in detail.

5.3 The link between Science and Technology

There is no general consensus about the nature and definition of technology. De Vries [2006] cites Mitcham [1994] to explain the varied understanding of technology. Mitcham argues that technology can be interpreted as "*object*" when referring to artefacts resulting from technological activity. Also, technology can be understood as "*knowledge*", meaning that technology is a "*discipline with a distinct kind of knowledge*" (p. 19). Also, Mitcham argues that technology can be taken as a "*process*" by suggesting that technology is the processes of "*designing, making and using*". Last, the author proposes that technology is an act of "*volition*", which means it is intentional, the product of will and choice. From Mitcham's point of view this renders technology as something that can be interpreted as part of the human culture. However, these distinctions do not compete with the idea that technology has the purpose of "*usefulness*".

The above suggests that technology goes beyond traditional definitions that associate it only with industrial techniques and machinery[13]. Furthermore,

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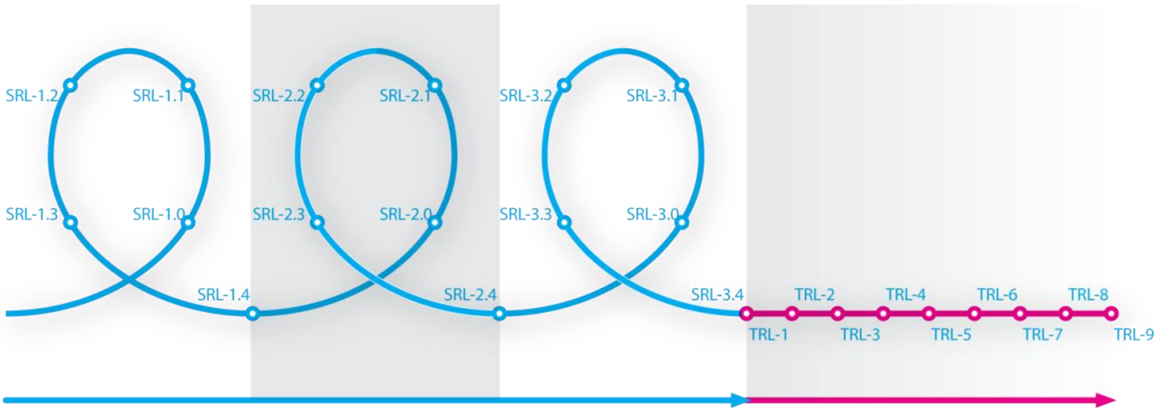
[13] Simon Collin's Dictionary of Science and Technology defines technology as *"the use of scientific knowledge to develop machines and techniques for use in industry"* (Collins [2007]).

technology can be interpreted not only as objects, knowledge, processes or volition as Mitcham suggested: it exists as a complex reality that interconnects all these elements. Kahn & Kellner [2006] emphasise the common mistake of exclusively associating technology with industry and cite Pearson & Young's [2002] argument that technology "*comprises the entire system of people and organizations, knowledge, processes, and devices that go into creating and operating technological artifacts, as well as the artifacts themselves*" (p.255).

Authors have linked the complex phenomenon of technology to scientific research. They establish a relationship of mutual benefit, where science feeds technology and technology feeds science in an iterative process. On the one hand, technological development sets directions for scientific research, as Nelson & Rosemberg [1993] (p. 7) illustrate: "*The advent of new technologies often leads to scientific work aimed at understanding these technologies, so as to enable them to be improved. Sometimes new technology leads to whole new scientific disciplines.*" Technology also enables advancement in scientific research, mainly by providing equipment and instruments for research; as an example of this Brooks [1994] explains: "*Technology has played an enormous role in making it possible to measure natural phenomena that were not previously accessible to research*". On the other hand, Brooks argues that science contributes to technological development as a *"direct source of new technological ideas"* and as a *"source of engineering design tools and techniques"*, or by providing *"Instrumentation, laboratory techniques, and analytical methods…for industrial processes and process controls".*

It has also been suggested that technology is the end result of scientific research. Mankins [1995] presents a linear model of technology utilised by NASA that splits technological development into technology readiness levels (TRL). The author explains that the model serves to assess specific technologies level of maturity, and to set comparisons between different technologies. This model proposes a level of basic technology research at the onset of technological development, and includes several stages or TRLs' that ends with the technology being qualified and proven.

Mills [2005], in an attempt to provide managers of a NASA long term and complex research project on making interstellar exploration practical, with a model to evaluate scientific progress, proposes a linear model of applied science readiness levels (SRL). The author suggests that the final and most advanced level of this model precedes the less advanced and first TRL. As suggested by Mills, Driver et al. [2012] integrates both models to show how technology is seen as the end result of scientific research.



Applied Science Readiness Levels

SRL 1. General physics
SRL 2. Critical issues
SRL 3. Desired Effect

SRL .0 Prescience
SRL .1 Problem formulated
SRL .2 Data collected
SRL .3 Hypothesis proposed
SRL .4 Hypothesis tested and results reported

Technology Readiness Levels

TRL 1 Basic principles observed
TRL 2 Technology concept formulated
TRL 3 Analytical/experimental concepts
TRL 4 Breadboard test in laboratory environment
TRL 5 Breadboard test in context
TRL 6 Subsystem prototype demonstration in context
TRL 7 System prototype demonstration in context
TRL 8 Actual system operational
TRL 9 Actual system proven

Diagram 5.8 *Integration of science and technology readiness levels according to Driver et al. [2012]*

Phaal et al. [2011], in an attempt to develop a framework for mapping science- and technology-based industrial emergence, also describe technology as a progression from scientific research. In their model, they 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.*”

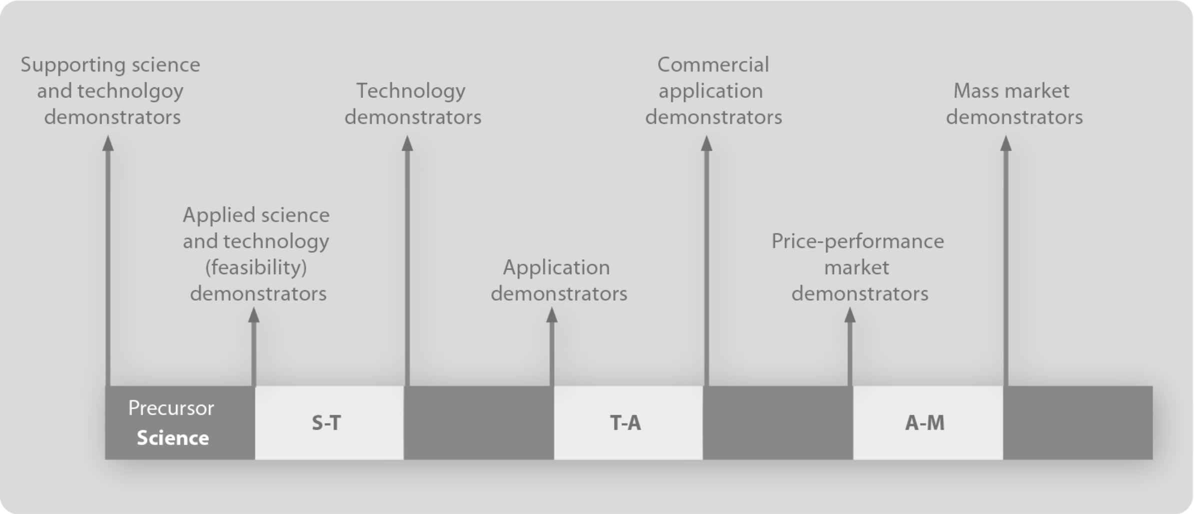


Diagram 5.9 *Science, technology, application and market linear model, adapted from Phaal et al. [2011]'s diagram of "Phases, transitions, milestones and trajectories of technology-intensive industrial emergence"*

Although these linear models hint on the idea of technological development being "fed" by science, other authors argue that technology has brought more to science than science to technology. For example Sismondo [2010] explains that although science and technology today are "*increasingly entangled*", science has not been necessarily a guiding force for technology, and that "*accounts of artifacts and technologies show that scientific knowledge plays little direct role in the development of even many state of the art technologies"* (p. 93).

Even if scientific research fed technological development and conversely technology fostered scientific research, advance in technology or science is not necessarily mutually dependent. Bauer [1992] (p. 125) argues that *"technology* *is not just applied science follows obviously (…) from the historical certainty that significant techniques are ever so much older than anything that one could call science*". Bauer also sets a clear distinction between applied science and technological development. While the purpose of the former is to achieve certain aims regardless of how beneficial they are, the later only develops if the premise of usefulness is met. This distinction reflects the differences in nature between science that seeks to understand the world, and technology that wants to render it useful. As Feenberg [2006] explains, "*Science and technology share a similar type of rationality based on empirical observation and knowledge of natural causality, but technology is concerned with usefulness rather than truth*" (p. 5).

Bauer also warns that confusing applied science with technological development fosters the mistaken idea that "*any advance in scientific research could be harnessed to useful application*" (p. 127). Additionally, he highlights the potential difficulties of an attempt to set up cooperation between science and technology, "*since the interest of one partner (science) is best served by complete openness while the interest of the other (technology) is best served by utter secrecy*" (p. 128).

From a different point of view, Stokes [1997] has developed a model to explain the relationship between scientific research and technological development (see Diagram 5.10). His model acknowledges the nonlinear relationship between science and technology, and their capability to progress independently from one another. Drawing on his Pasteur's Quadrant model, Stokes proposes a "*revised dynamic model*" that links scientific research to technological development. This model establishes two interwoven parallel streams in which paths of basic and applied research move from existing understanding and existing technology to improved understanding and/or improved technology. While Stokes' model also recognises that research for understanding and technological improvement can happen independently of one another, it acknowledges instances of interdependence, and sets use-inspired basic research as the key for the improvement of understanding and of technology.

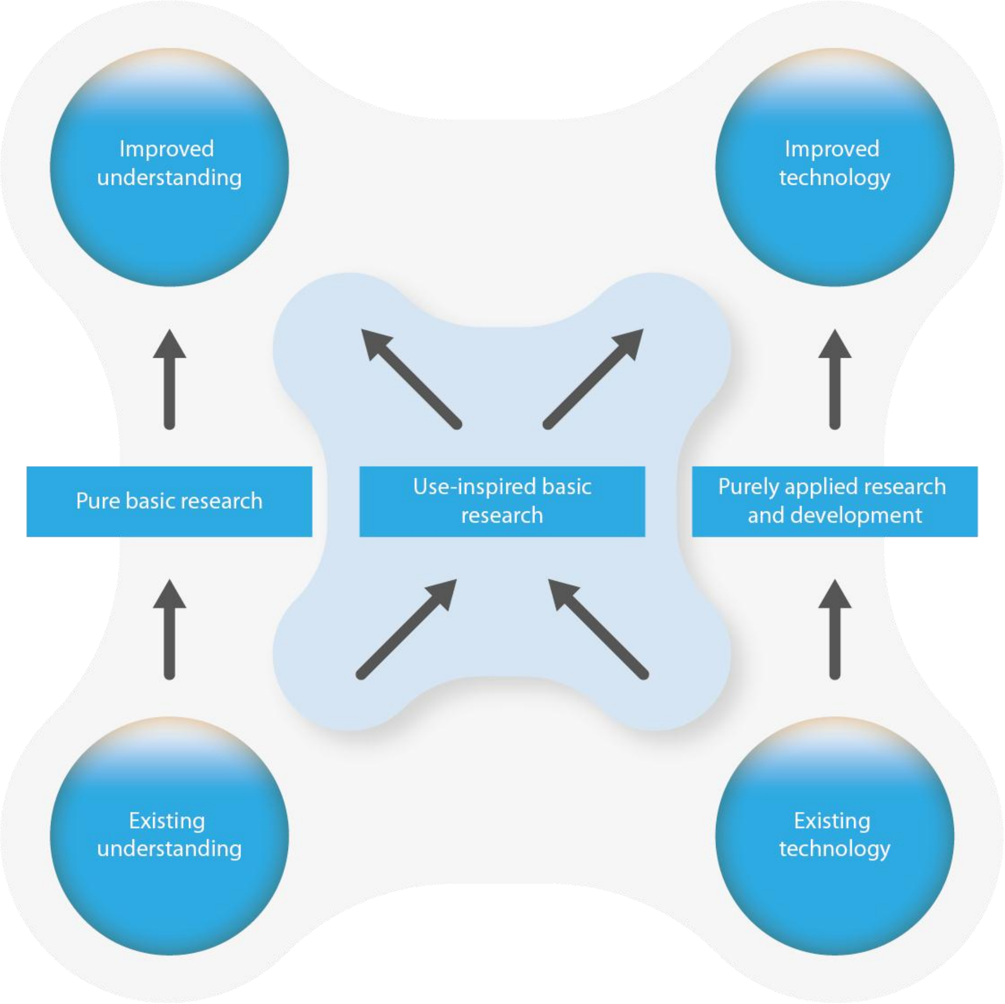


Diagram 5.10 *A revised Dynamic Model of Pasteur's Quadrant from Stokes [1997] (p. 88)*

Driver et al. [2011], in a similar line of thought, argue that scientific research can be an activity that is "*inherently iterative*", and that scientists move constantly from basic to applied research and vice versa. They found that iterative interaction between scientific research and technology "*give(s) rise to applications*" and suggest that the search for applications fosters research in science and technology, as illustrated in Diagram 5.11.

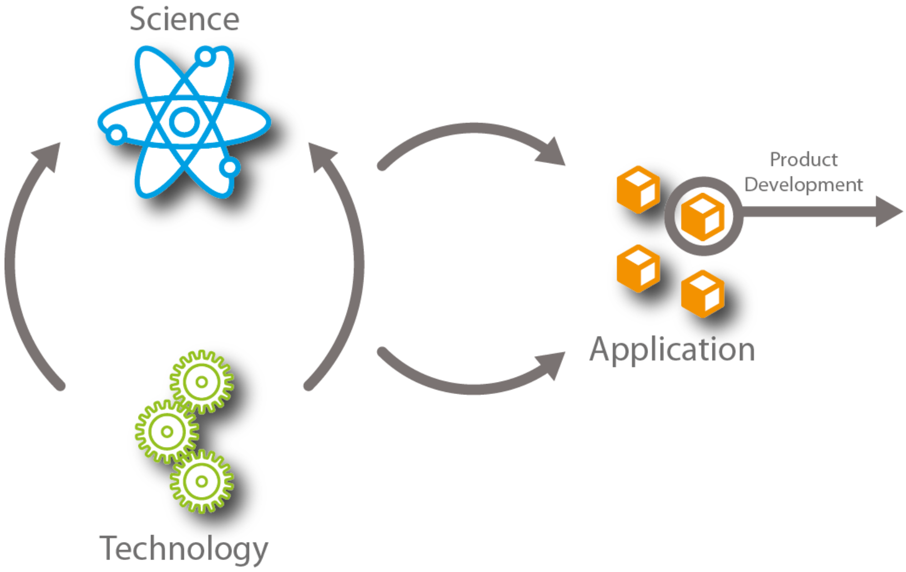


Diagram 5.11 *Driver et al.'s Model of scientific research in relation to Technology, from Driver et al. [2011]*

To conclude, it seems that although a distinction between basic and applied research can be made, in the day to day practice of science this differentiation is not perfectly defined. There is also an extra type of scientific research, the experimental, that seems to exist in the boundaries between scientific research and product/business development.

Even though scientific research and technology can develop independently from one another, scientific research in practice is closely linked to technological development. It seems that technology benefits from, and contributes to, all basic, applied, and experimental scientific research.

In all the models presented in this chapter, there seems to be an underlining principle that shows progression from basic research towards application. However, Stokes model identifies the important aspect of use-inspired basic research, which creates a link between basic research, applied research and the development of applications. Based on this and on the OECD model that also recognises applied research as a preceding step for the development of applications, a new model is proposed that connects basic and applied research to the development of application in a sequential order. The model shows how once principles are understood in the domain of basic research, they are tested and applied in the domain of applied research, and how this precedes the development of applications (Diagram 5.12).

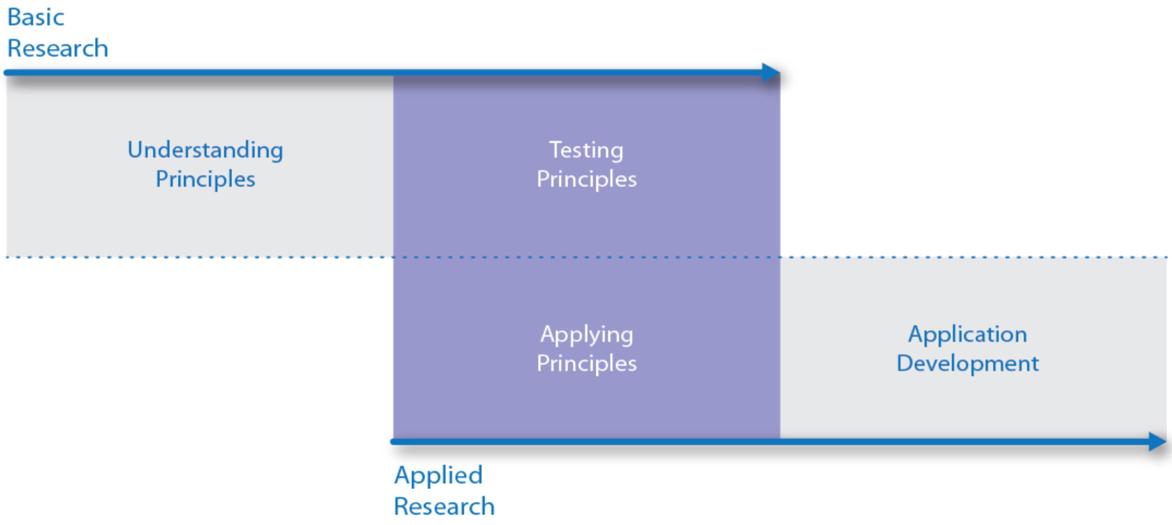


Diagram 5.12 *Map of scientific research (modified from Pasteur's Quadrant)*

5.4 Summary and implications

This chapter presents the idea that the linear model of scientific research is not a true reflection of what happens in science. It argues that scientific research practice can be affected by the personal and professional characteristics of the scientists, and that all scientific disciplines conduct research in different ways. It also argues that there are two dimensions to the practice of scientific research, one of a rational nature and the other of a social character. In the first, scientists conduct experiments, draw conclusions, set hypotheses, etc., in order to understand the phenomena they are studying. In the second, scientists write papers, prepare research proposals, work on research related presentations, etc., to communicate their findings to colleagues, the scientific community and the general public.

The existence of these two dimensions may be strongly related to the kind of contribution that designers can make to collaborative work with scientists. For example, designers could contribute to the development of testing devices for experimentation (rational) or to the design of visualization of scientific concepts to present at a conference (social). The case studies presented in later chapters of this thesis will explain how this happens.

This chapter also highlights the differences types of scientific research, outlining their main differences. This has implications for the study of collaboration between designers and scientists. Given that applied and experimental research is driven by considerations about use and applications, it is possible that designers find natural ways to contribute to these types of research. This is because, as seen in the previous chapter, usability is one of the designers' key areas of knowledge and expertise. In contrast, designers may find it difficult to contribute to basic research, where there is little interest in application and use and where all activity is centred on trying to understand phenomena.

This chapter also illustrates how scientific research and technological development relate to each other, arguing that they feed each other but can develop independently. It explains that inspired research can link basic scientific research and technological development. This has implications for the study of collaboration between designers and scientists as designers may be able to contribute in basic scientific research oriented towards technological development.

Following the examination in Chapters 4 and 5 of two of the main elements for the study of collaboration of designers and scientists in scientific research, the nature of design work and of scientific research, the following chapter will explore the last fundamental element: interdisciplinary. It will explain the different ways in which people from different disciplines can collaborate, such as scientists and designers, as well as the potential barriers to and enablers of this kind of engagement.

6. INTERDISCIPLINARITY

The previous chapter, "The nature of scientific research", identified two main dimensions that encompass scientists' activity while conducting scientific research: the rational and the social. It argued that these two dimensions are both linked to technological development. It also proposed that the contribution of design might vary depending on whether or not the scientific research is geared towards technological or theoretical development. The chapter also outlined what purposes scientific research can have: on the one hand, trying to understand, test and apply principles; and on the other, pursuing the development of applications.

In this way, the previous chapter demonstrated that scientific activity is substantially different to that of design. For this reason, and bearing in mind that design and science are both recognised as interdisciplinary activities (Shneider [2007]; Friedman [2003]), this chapter will analyse potential collaboration between these two domains through the lens of 'interdisciplinary collaboration'.

Rhoten et al. [2009] (p. 86) synthesised the work of various authors to produce a comprehensive definition of interdisciplinarity: *"The integration or synthesis of two or more disparate disciplines, bodies of knowledge, or modes of thinking to produce a meaning, explanation, or product that is more extensive and powerful than its constituent part, from Boix, Mansilla and Gardner, 2003; Klein, 1996; Kocklemans, 1979; Weingart and Stehr, 2000)"*. Thus, there are some core concepts that we can apply. First, the idea that interdisciplinarity demands two (or more) collaborating bodies. Secondly, that these bodies are from different domains. Thirdly, that the product of collaboration between these different bodies is better than it would be if approached from a single discipline. If we apply these concepts to this study, which looks at collaboration between members of two disciplines in an specific context (Scientific Research), interdisciplinarity refers to the combination of *different disciplinary expertise* (i.e. designers and scientists) in a *particular context* (i.e. scientific research) with the purpose of achieving *a unique and powerful result* (i.e. scientific discovery and application).

As a result, the present chapter attempts to contribute to the research analysis framework by identifying the main features of interdisciplinary collaboration. For this purpose, the chapter explains models of interdisciplinary collaboration and identifies potential barriers to and enablers of this type of engagement. It offers details on how these models can be utilised to understand aspects of collaboration between designers and scientists, arguing that they might not be individually comprehensive or contextually suited to the particularities of collaboration between designers and scientists. Consequently, the chapter proposes a new single model derived from these more generic ideas, which identifies the key categories of interdisciplinary work as applied to the relationship between designers and scientists (e.g. research focus, leadership, levels of participants' commitment and engagement, meaningfulness of contribution, team working structure and level of integration). This chapter concludes with a table that shows possible barriers to and enablers of collaboration, derived from relevant literature on interdisciplinarity.

6.1 Models for interdisciplinary collaboration

A number of different models have been proposed to classify interdisciplinary collaboration. Each of them has the potential to be used for framing and analysing interdisciplinary collaboration between designers and scientists. However, it seems that each one is only able to scrutinise certain aspects of collaborative work. For example, Klein [2005] presents Bass' [1975] classification of interdisciplinary collaboration (see Diagram 6.1). This classification is based on collaborative level of structuredness, constraints, control and orientation. In this categorisation, activity in interdisciplinary collaboration can be:

- *Un-oriented and unstructured*: Without a particular research focus and structure of work. It leads to better interdisciplinary understanding but seldom to useful results.
- *Oriented unstructured:* thematically more focused but still with unclear definition of programme and roles
- *Oriented structured without constraints*: common focus and programmed; "non-enforceable" leadership and loose subscription of researchers to set times and objectives
- *Oriented structured with constraints*: programmed to encourage direct contact and communication, generating consensus

- *Under centralized executive control*: carried out "under centralized administrative and operational control", it delivers concrete results but they can be limited in terms of creativity.[14]

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[14] Bass proposes this example to explain the categories:"*…a joint discussion of surgeons and engineers to consider an integrated approach to producing a new prosthetic device (Type II). The task may require general review of the diversity of skills needed (Type I). From this discussion, a consolidated program outline with a specific goal (Type III) might emerge. This effort, in turn, may be converted into a project proposal for outside support (Type IV). The activity will also include definition of objectives, justification of utility, designation of a project leader and other team members, a structured program, target date, and budget. In the end, an entrepreneurial manager will be needed with the authority to coordinate implementation (Type V)".*

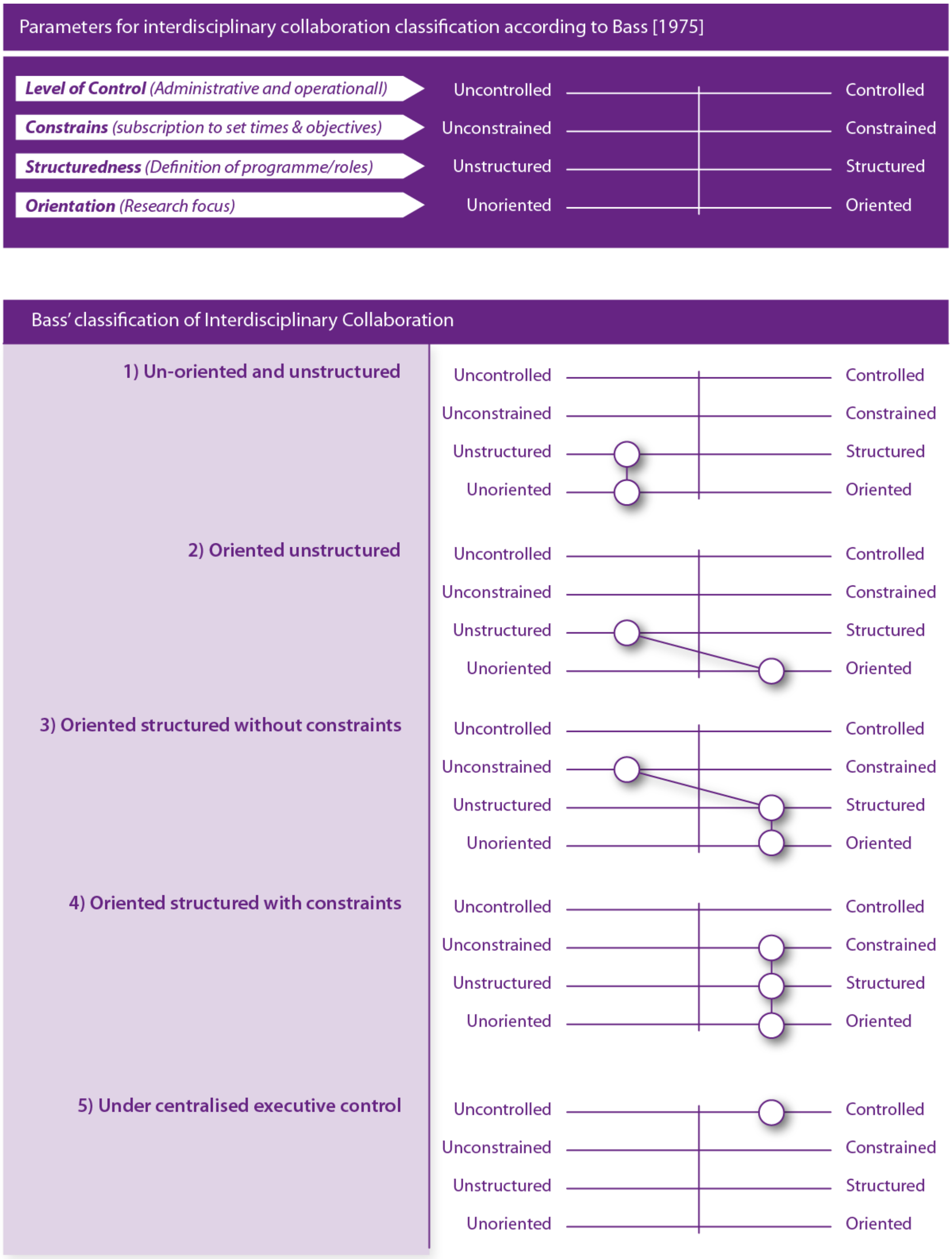

***Diagram 6.1** Visualisation of Bass's classification of interdisciplinary collaboration*

This classification is potentially useful to help to understand the nature of activities carried out in collaboration between designers and scientists, in relation to its orientation (research focus), structure (times/duration and participants role), constraints and leadership and organisational control. It also can help to understand whether these aspects have any influence on the potential success of collaboration and any issues or problems that may arise from it.

Bass's model does not consider the level of integration, interaction and contribution between collaborators from different disciplines. For this, Klein [2005] explains a categorisation by Simon & Goodge relating to levels of interaction in projects between disciplines that favour the use of quantitative methods and disciplines which utilise qualitative methods. Simon & Goodge establish four models of collaboration according to the integration of their participants' research methods:

- *Background or context information* in which contributions from researchers remain casual, are used only for reference, and are not part of the main study
- *Elaboration or explanation of findings* where qualitative results support quantitative as descriptive detail rather than findings
- *Definition of important variables or categories* in which qualitative research is employed to define parameters for quantitative research, but still remains as a subservient method to quantitative research

- *Creative combination of ethnography and multivariable approaches in research, analysis and interpretation* where both approaches, quantitative and qualitative, are integrated in order to answer the main research questions.

This categorisation can be used to compare the level of integration between designers and scientists in a collaborative endeavour, and to describe the extent of the contribution to research in relation to each discipline's approach.

Epstein [2005] presents John-Steiner's [1998] categorisation of interdisciplinary work according to patterns of collaboration (see Diagram 6.2). This categorisation looks at the level of formality and duration of the collaboration, at the level of integration of its members, at the formation of working roles and at the level of interdisciplinarity in the research output. Using these dimensions, Epstein proposed four different modes in which a collaborative activity might take place:

- *Distributed:* characterised by spontaneity, informality and centred on exchange of ideas and information. Roles of collaborators and working methods are spontaneous and responsive.
- *Complementary:* each individual contributes according to his/her own field of expertise. Roles are assigned according to individual strengths, knowledge and temperaments.

- *Family:* people “interchange roles” outside their own disciplinary boundaries. Groups are integrated horizontally and take decisions by consensus. Teams share common expertise.
- *Integrative:* long-term collective undertakings in which the roles are set by research questions and people’s experience rather than by disciplinary identities. Ideas and results are perceived as the property of the group, not of single individuals. New models of thought are constructed.

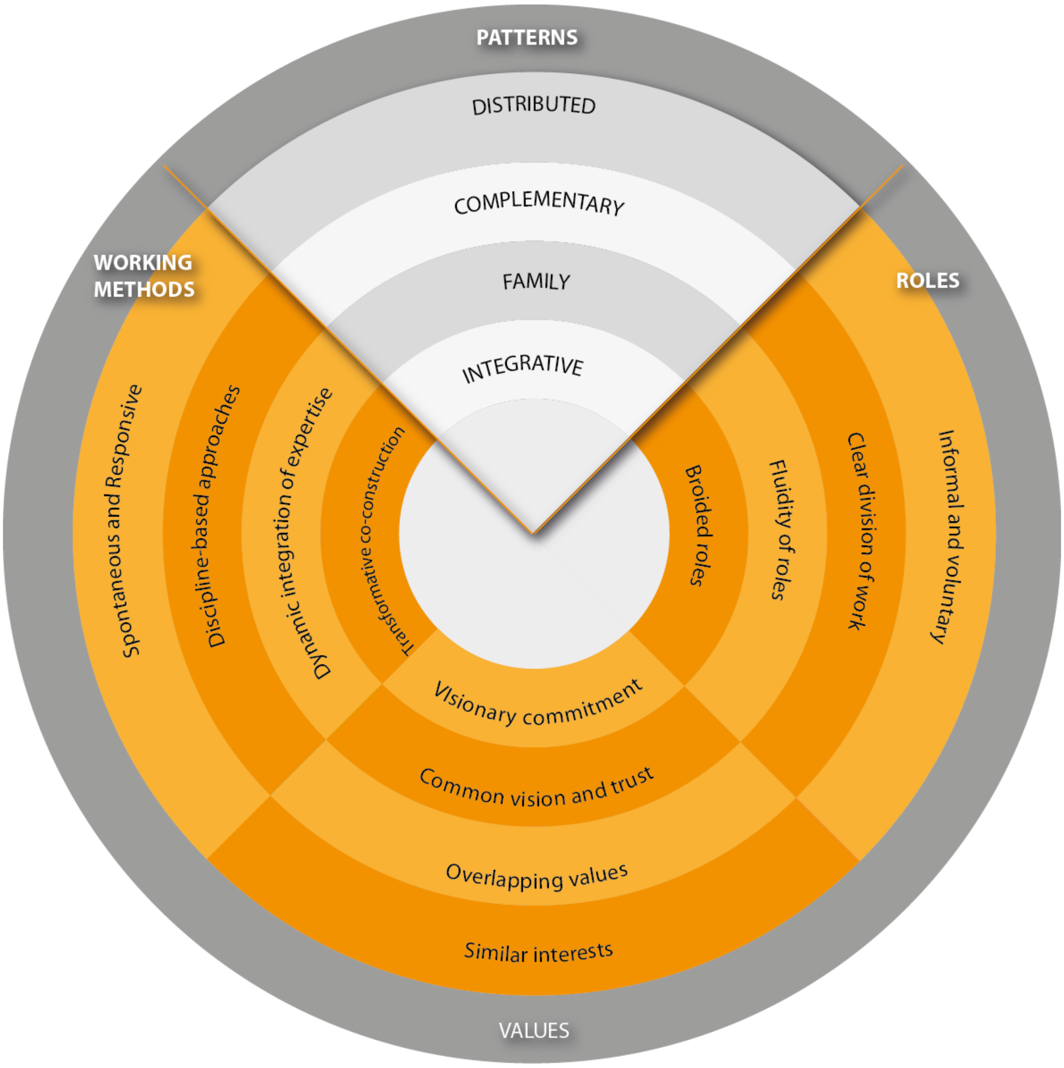

Diagram 6.2 *Collaborative Patterns based on John-Steiner [2000] (p.197)*

Although the previous models seem appropriate for looking at particular aspects of collaboration, they are generic and not specifically built to look at the potential particularities of collaboration between designers and scientists. Nonetheless, these models can be adapted to reflect the particularities of collaborative engagement between designers and scientists. John-Steiner's model seems to be especially adequate for this purpose.

As examined in Chapter 4, there are different factors that decide the way in which designers engage in collaboration. These factors are:

- The designer's entry point into the project: before, during or after the project formulation (Paton & Doors [2011])
- The designer's involvement in the identification of the problem (design opportunity) and/or in the formulation of the conceptual solution (design hypothesis) before the project concept development stage starts (Paton & Doors [2011])
- Determining who the project initiator is: the designer, the client or both simultaneously (Parsons [2009]).

Another factor that determines designers' engagement in collaboration is the role that the designers play in terms of their working function within the group. They can guide the group while giving design input (Design lead role), they can help the group to use design thinking (Teacher role), they can facilitate design work by setting an adequate work environment (Facilitator role) or they can orchestrate all design activity within the group (Director role) (Howard & Melles [2011]).

Following these factors, progression towards the highest levels of engagement, in which designers would be more integrated as researchers, disciplinary boundaries would tend to blur, and designers would have greater participation in deciding the research directions and a wider scope for their activity, would ideally imply: earlier designer entry into the project, greater designer involvement in both the definition of the problem and the formulation of the conceptual solution, and a shared responsibility in the initiation of the project.

Also, if designers and scientists are collaborating in the context of scientific research, it would be sensible to expect that the basic level of engagement would be similar to that of designers providing professional design services to the scientists, with the scientists acting as clients. Consequently, it would also be reasonable to imagine that the highest levels of engagement would imply both scientist and designers being integrated into a single research team, as suggested in Steiner's model when passing from "*complementary*" to "*integrative*" collaboration.

As a consequence of this, the following new model for collaboration between designers and scientists in the context of scientific research is introduced (see Diagram 6.3).

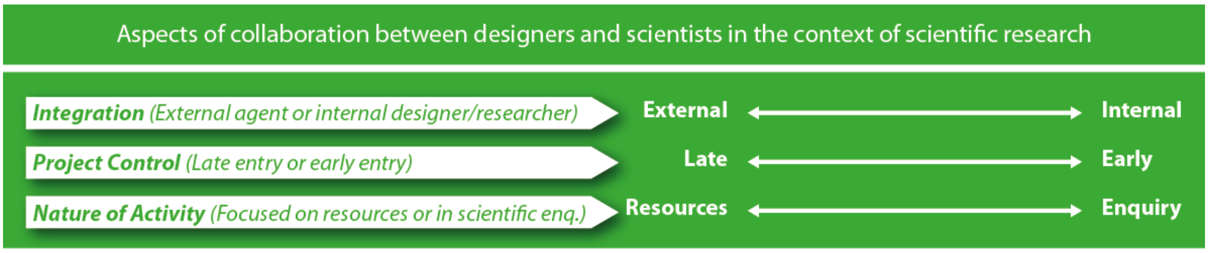

Diagram 6.3 *Aspects of collaboration between designers and scientists*

The model is built upon three main aspects:

- **Integration**: the designer acts as an external design supplier during the collaboration or else becomes an integrated member of the research team, acting as an internal Designer or Researcher. This aspect establishes whether the designer becomes a member of the research group or remains as an external agent during the collaboration. While external agents may work on specific predetermined projects, integrated designers may have a wider scope in their activity within scientific research activity.
- **Project Control**: the extent of the influence that the designers have on the definition of design priorities and the design brief. This is determined by how early designers are involved in identifying the issues to be resolved and in the formulation of conceptual solutions. On the lower level of engagement, designers are involved at a later stage in the process when the design problem has been already identified and a conceptual solution has been outlined. On higher levels, the designer makes an early entry into the project, when design issues have not yet been determined. Additionally, project control establishes whether the project has been initiated by the designer, the scientist or both.

- **Nature of Activity**: the extent to which design activity is focused on the resolution of issues directly related to the scientific enquiry or else geared towards the resources needed to conduct scientific research. It can range from the use of design tools and methods to address scientific research questions to the design of experimental equipment or laboratory spaces. The nature of design activity determines the extent to which disciplinary identities remain distinct or to which disciplinary boundaries are blurred. In the first extreme, designers design equipment, spaces, etc and keep their disciplinary identity (while scientists conduct scientific activity). In the second, designers would undertake scientific activity using design capability as a resource (and the scientist might integrate design tools and methods to conduct scientific activity)

An initial overview of this model, which follows a similar structure to the visualisation of Bass's model created by the author of this thesis, underpins a hypothetical categorisation of designers' engagement with scientists in scientific research. This categorisation is the basis for analysis and comparison with case studies in further chapters of this thesis (see Diagrams 6.4 to 6.7).

This model initially proposes four levels of research engagement. These levels are explained below, accompanied by diagrams for reference. On the left hand side of each diagram, there are three lines with circles that indicate the integration, project control and type of activity. This is done by locating the circles on the side closest to the concepts that best describe each of the aspects. On the right hand side, there is a descriptive pictogram of the collaboration. The figure in black represents the designer and the figures in white the scientists (at level 4, the figure in white wearing red glasses represents a researcher with a design background). The green area represents the team (team membership). The cube with the 'D' represents the design problem (issue) and the atom the scientific question (enquiry). The dotted line represents a boundary between researchers (right) and non-researchers (left).

Level 1 - Design Supplier: Collaboration in which the designers act as external "design suppliers" and in which the design issues and initial conceptual solutions are determined by the scientists from the research group. The design tasks are not directly related to the research questions, and focus on improving the resources associated to the undertaking of scientific research. Designers have no research membership.

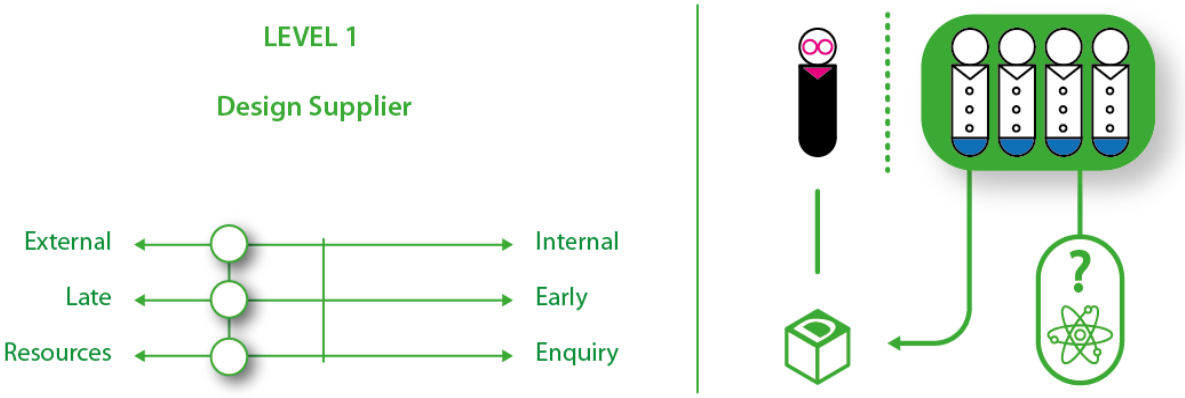

Diagram 6.4** Level 1 - **Design supplier

Level 2 - Team Member: Designers are members of the research group, and have a wider scope in their activity within scientific research activity. Yet their role within the group is to be "the designer" and not a researcher. Tasks are still not directly related to the research questions, and scientists continue determining the design issues. Designers can formulate conceptual solutions.

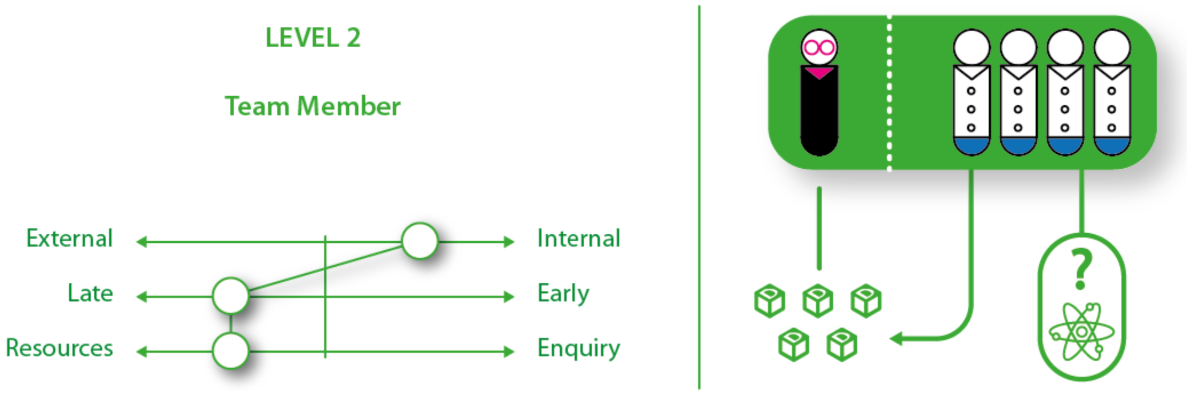

Diagram 6.5 *Level 2 -* ***Team Member***

Level 3 – Embedded Designer: Collaboration in which designers (or designers and scientists jointly) determine design issues and formulate conceptual solutions. The designers' activity remains focused on the development of resources, and disciplinary roles remain discrete even though the designers are members of the research team.

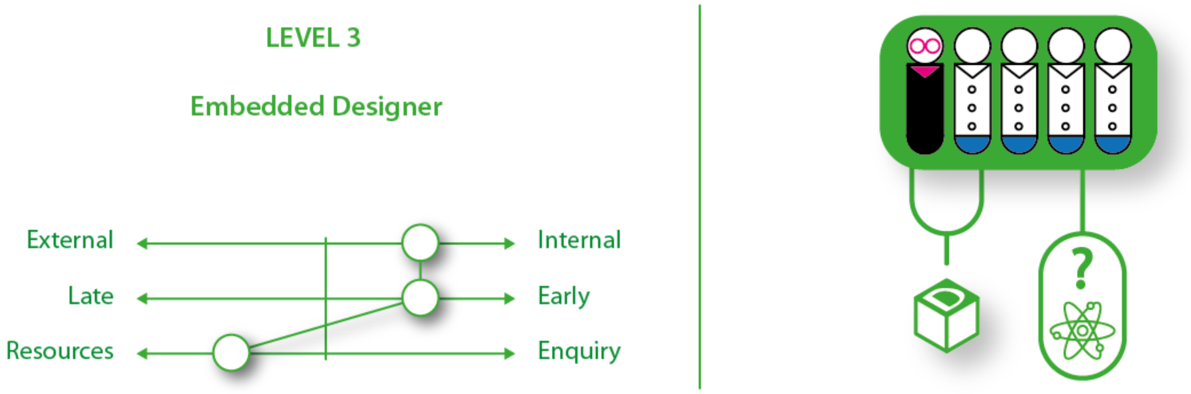

Diagram 6.6 *Level 3 -* ***Embedded designer***

Level 4 – **Team researcher:** Collaboration in which designers and scientists team up to address research questions. Disciplinary roles are blurred and activities are defined by research questions and by researchers' experience. Designers become researchers with a "design background". At this level, full interdisciplinary integration has been achieved.

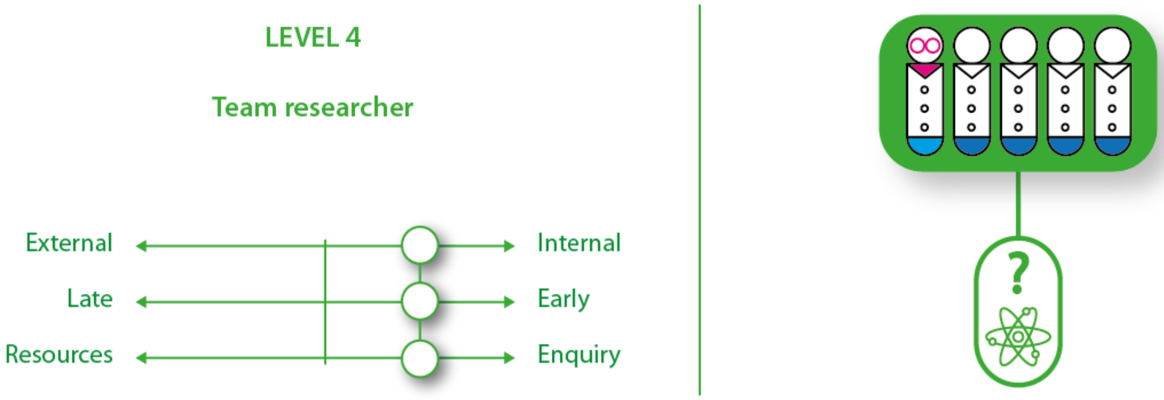

Diagram 6.7 *Level 4 –* ***Team Researcher***

6. 2 Barriers in interdisciplinary collaboration

The literature on interdisciplinarity underlines the importance of the identification of potential problems in collaborative work. For instance Klein [2005], a leading author in factors and issues relating to interdisciplinary collaboration and surveying practices in science, industry and government, presents an extensive and comprehensive list of potential problems in interdisciplinary collaboration. Klein explains that barriers can be created by factors such as the personal characteristics and attitudes of the researcher, the context in which the research is carried out (physical, institutional, work, legal, etc.), the disciplinary background of the researchers and their inherent perception of the world, and the group dynamics. These factors can be associated to a greater or lesser extent with Klein's lists of potential problems:

- Social and psychological impediments, such as resistance to innovation, mistrust, insecurity, marginality
- Participants may lack integrative skills, system thinking, and familiarity with interdisciplinarity
- Strong groups can be undermined by unstable membership and unwillingness to take risks
- Projects can face time and access to equipment constraints, rigid budget and administrative categories or restrictive legal mandates and policies
- Progress can be deterred by lack of incentives and inadequate reward systems
- Disciplinary defaulting can happen
- Conflict may appear over technical issues (definition of problems, research methodologies, and scheduling) or be associated with interpersonal issues (leadership style and disciplinary ethnocentrism)
- "Excessive organisational baggage" as evidenced in fixed perception by others, issues of status within the organisation, preconceived ideas of roles and different understanding of problems

From a different perspective, Reich & Reich [2006] identify the struggle for power as a source of conflict in interdisciplinary work, highlighting "tokenism" (disciplines represented in teams but not included in the decision making processes), and the silencing of “lower status” disciplines by hierarchical structures. The authors also highlight “disciplinary policing”, or reinforcement of discipline boundaries grounded in participants’ belief of a “disciplinary superiority”.

From a study on the search and selection of partners for collaboration, Spallek et al. [2008] build another list of barriers to the formation of collaboration. Some of the items on his list are already included in Klein’s list, but a few of them are not. The nature of these problems seems to be associated with the level of preparation for collaboration before it actually begins. For example, collaborators may have a *“lack of situational awareness”* when they are new to the host organisation or research group. If the collaboration setting were adequately prepared, there would be mechanisms in place to welcome and train new researchers in order to facilitate their quick and smooth integration.

It is likely that collaboration between designers and scientists could be hindered by any of the problems identified in this section. However, there may be other as yet unidentified problems inherent in collaboration between designers and scientists. For example, as suggested by Rust [2007], designers and scientists can have difficulty in communicating, due to the lack of a common specialist language. They can also have difficulty in making tacit contributions explicit.

Table 6.1 presents a summary of the possible barriers to interdisciplinary collaboration; the barriers have been clustered in groups according to their thematic similarities. Five main clusters have been identified:

- Context
- Group dynamics
- Collaboration preparedness
- Personal characteristics and attitudes
- Disciplinary background

This table will be reflected on in later chapters in order to identify which known or emerging problems might influence collaboration between designers and scientists.

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Table of Barriers to Interdisciplinary Collaboration

		C	GD	CP	P&A	DB	K	R	S
C	Projects can face: Time/access to equipment constraints, rigid budget and admin categ. or restrictive legal mandates/policies	●		●			●		
	Progress can be deterred by: Lack of incentives and inadequate reward systems	●					●		
	“Excessive organizational baggage”: Fixed perception by others, status in the organization, preconceived ideas of roles, etc.	●	●		●		●		
	Undersized social network (Opposes to Klein *“Excessive organizational background "*)	●			●				●
	Lack of physical proximity	●							●
	Not getting access: *"Competition for Peoples time and attention "*	●		●					●
GD	Strong groups can be undermined by: Unstable membership and unwillingness to take risks		●				●		
	Conflict may appear over technical issues (def. of problems, research meth, etc) or interpersonal issues (leadership style,etc)	●	●		●	●	●		
	Tokenism: Disciplines represented in teams but not included in decision making processes		●					●	
	Hierarchical structures silencing “lower status” disciplines	●	●			●		●	
	Disciplinary policing/disciplinary superiority bulling		●		●	●		●	
CP	Participants may lack: Integrative skills, system thinking, and familiarity with interdisciplinarity			●		●	●		
	Lack of situational awareness: Lack of orientation of newcomers in organizations/research groups			●					●
	Lack of mutual advantage: Unfair distribution of benefits amongst collaborators			●					●
	Interferences with research from other duties the researcher may have.	●		●					●
P&A	Social and psychological impediments: Resistance to innovation, mistrust, insecurity, marginality				●		●		
	Limited transaction memory: Unawareness of other people’s knowledge				●				●
	Social overload: Senior researchers reluctant to collaborate.				●				●
	Status differences				●				●
DB	Disciplinary defaulting can happen		●			●	●		
	Little terminology knowledge			●	●	●			●

C: Context GD: Group Dynamics CP: Collaboration Preparedness P&A: Personal Chracteristics & Attitudes DB: DIsciplinary Background

K:Klein (2005) R:Reich (2006) S:Spallek et al (2008)

Table 6.1 *Barriers to interdisciplinary collaboration*

6.3 Enabling collaboration

Investigating the problems that may arise during interdisciplinary collaboration seems to be important in understanding collaboration between designers and scientists. Furthermore, by understanding these problems, it is likely that the subsequent identification of enablers arises by default. For example, if a lack of common language is identified as a problem for collaboration, then it can be concluded almost immediately that the construction of a common language is a collaboration enabler. However, there are studies that look exclusively at ways to improve collaboration.

Epstein [2005] for example, examines different aspects of interdisciplinary work and puts forward suggestions for enabling and enhancing collaborative work. She looks at the attitude of researchers, suggesting that they need to be receptive, open minded (especially with regard to other disciplines), ready and proactive in learning from others, and to have a sense of humour. She highlights that personal empathy between researchers plays an important role in the success of scientific research. Epstein also looks at communication, proposing that "*fundamental terminology should be established early on and reviewed regularly*" and that particular attention should be paid to unnoticed specialised use of same words that have different meaning in each discipline. She also comments on time, explaining that interdisciplinary collaboration demands more time than intra-disciplinary work would normally do to achieve the same goals, so special care should be taken when preparing research budgets.

Epstein emphasises the importance of proximity between researchers, arguing that face-to-face contact is fundamental for interdisciplinary collaboration. Mentioning the importance of having institutional support, Epstein asserts that interdisciplinary research requires more funding than disciplinary research (to pay for the integration costs) and that it is more difficult for interdisciplinary research groups to obtain funding. Epstein examines the importance of roles in interdisciplinary work. She suggests that it is important to ensure a clear allocation of responsibilities, and proposes that it is vital to have a leader to "define the common problem and the language in which to discuss it, to set priorities, and even to target publications" (though the group may opt for an equally valid model in which decisions are taken by consensus). Also, she suggests that someone should have the role of "facilitator" to ease communication between members of the team. Finally, Epstein explains that the research topics should be equally interesting for all disciplines involved and that, ideally, none of them should be closer than the others to a solution at the beginning of the collaboration.

A different view of enablers of collaboration comes from Crow et al. [1992], who examine collaboration in the context of interdisciplinary research. The authors, who come from the different disciplines of anthropology, psychology and sociology, reflect on their own interdisciplinary study of a group of education students who left their original professions to become teachers. Their study draws conclusions on "*what facilitates and constrains the successful conduct of collaborative interdisciplinary research*". Crow et al. base their position on John Mergendoller's view, which identifies three essential points for conducting successful interdisciplinary collaborative research: parity, reciprocity and a common language. Parity refers to the idea of finding a balance for the contribution that researchers with different disciplinary background bring to the research; that is, competing disciplinary points of view should be weighted by the team and balanced to serve the research while keeping the researchers happily involved. Reciprocity involves giving something back to the subjects under study by sharing with them the research developments and findings (applicable only to qualitative research studying people). The notion of a common language addresses the problem of the different meaning of similar words in different disciplines. Crow et al. argue that making explicit the meaning of certain key words makes collaboration easier. They also suggest that the discussions that help to reveal these meanings can add new knowledge and positively influence the direction of the research.

Examining collaboration between social and natural scientists, Balstad Miller [1994] looks at the challenges of interdisciplinary collaborative research on the subject of global environmental change. She comments on the increasing need for truly interdisciplinary work to deal with the complexity of environmental phenomena. She explains that, more than relating to the potential of different disciplines to make a valid scientific contribution, problems in collaboration are more likely to be associated with "*the attitudes and beliefs that participants in the research bring to the table*". Balstad Miller identifies three main actions that enable collaboration in this context. First, "*once there is agreement on collaboration, there must be a new* *conceptualization of the research problem*". In this way, all researchers will be able to contribute from their respective fields. Secondly, there must be an "*agreement on measurement*". This is important because without it "*scientists will face serious analytic problems*" when it comes to examining and reflecting on the data collected. Finally, it is fundamental to allow enough time for the collaboration, so that the researchers involved can become familiar with the "*substantive concerns and research methods*" of their colleagues. An initial extra allocation of time to allow for researchers' mutual knowledge and adaptation might make the collaboration longer but also probably more effective in the long term.

Table 6.2 presents a summary of the possible enablers of interdisciplinary collaboration, clustered in thematic groups. The table indicates when an enabler is common to two or more thematic groups. This table will be reflected on in later chapters to identify which known or emerging enablers might influence the collaboration between designers and scientists.

Table of Enablers for Interdisciplinary Collaboration

		A	C	A&P	CS	E	C L & N	B
A	Being receptive, open minded , ready and proactive in learning from others, and having a sense of humour.	●				●		
	Personal empathy between researchers	●				●		
C	Fundamental terminology established early and reviewed regularly		●		●	●		
	Attention paid to unnoticed specialised use of same words that have different meaning in each discipline		●					
	Developing a common language and making explicit the meaning of certain key words		●				●	
A&P	Research topics are equally interesting for all disciplines involved			●	●	●		
	Reciprocity: giving back to the subjects studied by sharing with them the research developments and findings			●			●	
	Parity: competing disciplinary points of view should be weighted by the team and balanced			●			●	
	Agreement on measurement must be reached			●				●
	Reformulation of research problem inmediately done after an agreement on collaboration has been reached			●				●
CS	None of the researchers closer than the others to a solution at the beginning			●	●	●		
	Clear allocation of responsibilities				●	●		
	Having a team leader or a work model in which decisions are taken by consensus			●	●	●		
	Having a "facilitator" to ease communication between members of the team				●	●		
	Initial added time for researchers' mutual knowledge and adaptation		●		●			●

A: Attitudes C: Communication A&P: Approach and method CS: Collaboration settings

E: Epstein (2005) C, L & N : Crow, Levine & Nager (1992) B: Balstad Miller (1994)

***Table 6.2** Enablers of interdisciplinary collaboration*

It is possible that designers may have some inherent generic characteristics that help them to engage effectively in collaborative activities. For example, their "attitude" can be an advantage to collaborative work, since they "*can communicate with all specialisms... (and) integrate the (often mismatching) inputs from specialisms*" (Stappers [2007]). It also seems that designers may be naturally suited to play the role of facilitator within research groups, given their abilities to communicate not only by conventional means but also through visual methods. It is worth mentioning that some designers' "generic characteristics" such as the ability to facilitate, can be affected by the "individual personality" of each designer. So when examining enablers, a clear distinction between designer's traits that are and are not affected by the designer's personality should be drawn.

It is also important to pay attention to two other aspects mentioned by Epstein [2005]. First, if a scientist takes the role of leadership within an interdisciplinary scientific research group, the group should be careful to avoid hierarchical structuring which results in designers losing decision-making power on design-related issues. Secondly, collaboration between designers and scientists in the context of scientific research may not always have a single common research interest for all participants. For this reason, designers and scientists may have to maintain effective group communication and to make additional efforts to keep the research useful for the whole group.

6.4 Summary and implications

This chapter shows models that can help to explain collaborative work and draws from them a new suitable model for collaboration between designers and scientists. It also presents potential barriers to collaboration, emphasising how they relate to collaboration between designers and scientists. In addition, the chapter explains how collaboration can be enhanced by paying attention to researchers' attitudes, communication strategies, role settings, and research topic choices. The section also explains how designers have certain characteristics that make collaboration easier for them.

On balance, the argument suggests that interdisciplinary studies may be useful to support the study on collaboration between designers and scientists, and in particular to resolve the following questions:

What is (are) the role(s) that a designer can play in interdisciplinary collaboration with scientists in the context of scientific research?

Can designers get directly (or indirectly) involved in the resolution of scientific research questions? And what are the disciplinary boundaries of their contribution?

What are the main barriers and enablers in collaboration between designers and scientists in the context of scientific research?

With this and the three previous chapters, this thesis attempts to construct an analysis framework for understanding the collaboration between designers and scientists undertaking scientific research. This framework will underpin the case studies included in this research. The following chapter will present a mapping and recording tool created both to record and map the case studies conducted to support this research, and for use as a visual aid to analyse the results of the case studies.

7. CASE STUDIES

This chapter reports on five case studies carried out with the purpose of obtaining empirical evidence to support the claims of this thesis regarding collaboration between designers and scientists in scientific research.

As explained in Chapter 2, the case studies were conducted in two stages. The first stage included 3 *exploratory case studies* and the second comprised 2 *development case studies*. While the exploratory cases dealt with scientific research in various stages, the development case studies were concerned with scientific research in its early stages.

7.1 Exploratory Case Studies

These cases were selected from a range of case studies offered by the UTTO so that a) the design team could provide a meaningful design intervention, and b) the nature of the research needs, and subsequently of the design intervention, would be different in each case.

As previously stated, the overall purpose of the exploratory case studies was to enable an initial analysis of the potential impact of design expertise and to help focus the research objectives.

In particular these case studies were conducted in an attempt to gain a first insight into what the practice of scientific research means in reality and to obtain first impressions of the type of contribution designers may make in scientific research. They also aimed to provide an initial understanding of the possible modes of engagement between designers and scientific research teams, as well as of the possible barriers to and enablers of collaboration.

The exploratory case studies also intended to provide the research team with an initial understanding of scientists' expectations regarding collaboration with designers. Furthermore, the cases aimed to give the research team a sense of scientists' receptivity, openness and willingness to be involved in such engagements.

In addition, the case studies had operational objectives. In this sense they aimed to consolidate and make operational the design team and to create a portfolio of design capability for further case study "recruitment". Also they intended to initiate the development of a network of stakeholders from the design and scientific community that might be useful in further research. Last, these exploratory case studies were set to make possible a better understanding of the conditions such as duration, type of projects, resources, etc., in which further case studies should be carried out.

The exploratory case studies included:

***Case 1* (Mask),** entailing the development of a device for the testing of a medical scientific hypothesis; ***Case 2* (Immunoassay),** including the design of systems and devices to reduce the time taken to perform a laboratory analysis technique; and ***Case 3* (Multistable material),** involving the development of a new technique of forming multistable structures from a variety of materials.

7.2 Development Case Studies

One of the case studies was selected from a range offered by the UTTO and the other came from contact with a scientist interviewed at the beginning of the research. These cases were chosen a) so that the design team could have a longer and deeper engagement with scientists, and b) to make it possible to explore and compare case studies in which the collaboration departed from either an identified design need or from an unidentified one.

As stated before, the general purpose of the development case studies was to examine the potential contribution of designers collaborating with scientists in the context of scientific research, specifically in its early stages. The exact point was gauged by the scientists' own perception of their research. In both cases the scientists stated that their research was in early development and far from any possible commercial application.

Specifically, these case studies were conducted in an attempt to obtain new insights into the type of contribution designers may make in the context of scientific research, and to gain understanding of the possible modes of engagement between designers and scientific research teams working on the early stages of scientific research. They also aimed to provide initial understanding of the possible barriers to and enablers of such collaboration. Last, the case studies aimed to explore designer contribution to cases in which the design need or scope was principally identified by either the scientists or by the designer.

The development case studies also intended to allow the building of a solid working partnership between designers and scientists without the immediacy and restrictions of a short project, and those constraints derived from single previously specified design needs.

In addition, the development case studies also had operational objectives. In this respect they intended to expand the variety of collaboration output and to generate rich and extensive data for analysis.

***Case 4* (Biophotovoltaics),** involved the development of design concepts for future application of biophotovoltaic technology and the design and manufacturing of demonstrators for the technology and its potential application; ***Case 5* (Stem Cell),** included the design of a communication tool for scientists undertaking research on stem cells.

Table 7.1 summarises all the case studies.

Case studies summary

EXPLORATORY	Case study	Main design task	Main scientist(s) background and number	Department	Duration	Origen
	MASK	*Development of a* **mask for respiratory therapy**	Experimental Medicine (1)	Addenbrookes Hospital	8 months	UTTO
	IMMUNOASSAY	*Design and manufacture of a prototype* **fluid handling System for Immunoassays**	Biochemistry (2)	Chemical Engineering and Biotechnology	9 months	UTTO
	MULTISTABLE MATERIAL	Development of a **wearable application of a multistable material**	Engineering/ Material Sciences (1)	Engineering	4 months	UTTO

DEVELOPMENT	Case study	Main design task	Main scientist(s) background and number	Department	Duration	Origen
	STEM CELL	*Development of a* **communication tool for stem cell researchers**	Biology and Genetics (2)	Laboratory for regenerative medicine	15 months	UTTO
	BIOPHOTOVOLTAICS	*Application exploration and development of* **biophotovoltaic technology**	Chemical Engineering Plant Sciences Biochemistry (1)	Chemical Engineering and Biotechnology, Biochemistry and Plant Sciences	20 months	Interview

Table 7.1 *Case studies summary*

Different activities were carried out in each case study, and the project participants changed for each activity. Regarding the composition of the participants in each of the activities, there were 4 permutations: 1) design team only; 2) scientists only; 3) design team and scientists; 4) extended project team (with guest designers and scientists).

The activities related to the case studies were:

- *Exploratory meeting:* to understand the nature of the scientific project, to understand the perceived design need and to determine whether or not the project matched the research team's expectations (project team)
- *Brief development*: to set the project's objectives, stages, timetable and deliverables; also to verify the correct understanding of the relevant science by designers (design team)
- *Briefing meetings:* to discuss and agree on the design brief for the project (project team)
- *Visits to labs/field:* to understand scientist/user requirements; these visits included participant and non-participant observations (project team, or design team + scientist(s))
- *Online research:* to explore design work already developed on the field, and to improve/confirm designer understands of relevant scientific concepts
- *Desk work:* to prepare presentations, reports, papers, briefs, computer drawings/plans, etc (design team)
- *Brainstorm/design focus sessions:* to generate/discuss ideas (design team, or project team, or extended project team)

- *External Expert consultation:* to obtain advice on project-related matters in which the design team and the scientists did not have expertise (design team and experts)
- *Design development sessions*: to transform initial ideas into workable concepts and to develop them (design team)
- *Workshop/laboratory work:* to make sketch models, to produce prototypes and to test ideas (design team, or project team, or design team + scientist(s))
- *Outsourcing work:* to produce printed material and 3D elements such as moulds and rapid prototyping pieces
- *Interim meetings:* to report, discuss project developments (project team or scientist + design team)
- *Presentations:* formal communication of design work/ideas (project team)
- *Exhibition design and setting:* to exhibit research output in national and international design trade fairs and events (design team and scientists)
- *Dissemination activities:* to present research output in different media such as live TV programmes, blogs and Facebook pages; to include research output in design and scientific magazines both online and in print, and to have it featured in published books (design team and scientists)
- *External recognition activities:* to receive design prizes for research output.

In addition to these activities, designers and scientists were in contact through phone calls and emails, and through exchange of digital files. Also, models and prototypes were passed to and from designers and scientists while conducting technical and usability tests.

Notes, tape and video recordings were taken during meetings and work sessions. Initial and follow up semi-structured interviews with the participant scientists were recorded and a physical collection of cognitive artefacts (designers sketches, models, prototypes, etc) and design outputs was made. Design team follow-up discussions were carried out immediately after each meeting, presentation and work session. Written case reports were produced and the project team was invited to comment and check for any errors in perception or interpretation.

The mixed data sources were analysed to determine patterns, common issues and differences among the case studies. Analysis was carried out mainly through narrative reconstruction of the study cases, using recordings, documents and design outputs to trigger memories and reflections.

In the following sections of this chapter, a description of all case studies will be presented. For that purpose, each case study will include 3 parts. The first part is called *the Collaboration Context*. It offers relevant details about the scientists' research to explain their reasons for engaging in collaboration with designers. The second part is named *the Design Process*. In this section a description of the project undertaken by designers and scientists is made, presenting a sequential account based on a retrospective review of the projects. These first two parts are accompanied by a collaboration matrix, which is designed to map collaboration in respect to the design process and to the scientific process, making it possible to visualize how those processes have affected each other, and identifying points and areas of interaction between designers and scientists. The last part of each of the case studies, *Collaboration Output and Outcomes,* presents the results of the collaboration.

The case studies have all been described based on a retrospective review. This review was undertaken by the design team in sessions dedicated to recalling the case studies, their sequence and their participants, and to annotating all the activities developed during them. This was subsequently mapped on the collaboration matrix. The first drafts of these memory exercises mapped on the collaboration matrix were then taken to the scientists to discuss the accuracy of the description (and also the accuracy of the matrix regarding its description of the scientific research process). With a final corrected version of the matrix for each of the case studies, additional and complementing data was extracted from other resources such as:

- Taped interviews with the scientists before, during and after the case studies
- Taped recordings of different meetings occurred during the case studies
- Electronic communications between all participants in the case studies
- Design notes, sketches, models, design briefs drafts and final documents.

7.3 The Collaboration Matrix

The collaboration matrix is a mapping instrument created to make visible how the design activity and the scientific research processes happen in the context of collaboration between designers and scientists. In particular, the collaboration matrix aims to make possible the mapping of:

- Design or scientific activities
- People (designers or scientists) involved in the activities

- Relationship between activities and the design process and or the scientific research stages
- Sequence and synchronicity[15] of activities.

The collaboration matrix was also developed to make possible the visualisation of the interdependence of design activity and scientific research during collaboration, and the identification of initial patterns, similitudes and differences between different case studies.

The collaboration matrix was inspired by the work developed by Mackay & Fayard [1997] in their paper "HCI, Natural Science and Design: A framework for Triangulation across Disciplines". The authors, seeking to explain how the field of Human Computer Interaction (HCI) integrates design and scientific activity, developed a model of representation/framework in which it is possible to link different levels of work through an interconnected sequence of tasks. In their framework, they represent 3 main levels of work (Theory, Design of Artefacts and Observation) as parallel sections in which boxes (representing activities), interconnected through arrows (representing sequence and paths), are sufficient to describe 6 different HCI projects involving a wide variety of design and scientific activities (Diagram 7.1).

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[15] Synchronicity refers here to identifying whether two activities are or not happening at the same time and whether there is any overlap in activities.

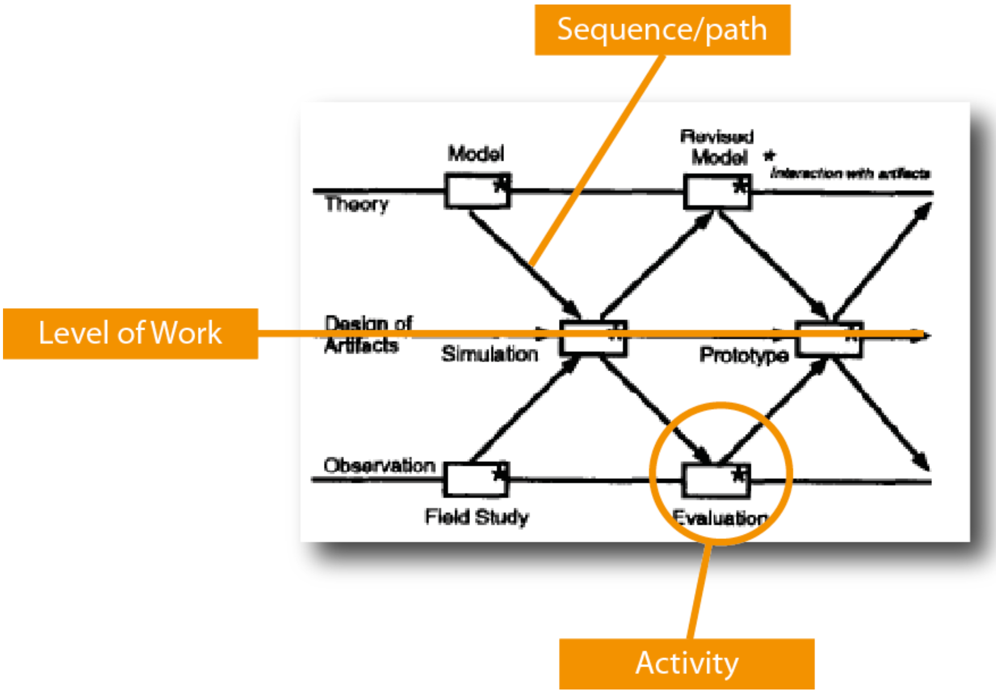


Diagram 7.1 *Diagram of integration of design and scientific activity from Mackay & Fayard [1997] (p. 6)*

Since this model was set up to explain HCI projects involving design and scientific activity but not collaboration between designers and scientists, it was adapted into a new model that made it possible to map both scientific research and design work processes. For this, both activities were divided into levels of work: first, in order to allow the collaboration to be mapped with great accuracy in relation to how far the scientific activity had progressed; and secondly, to illustrate which dimension of scientific research was influential. Also, the split aimed to make possible the visualisation of the impact that the different stages of the design process would have in different aspects of scientific research.

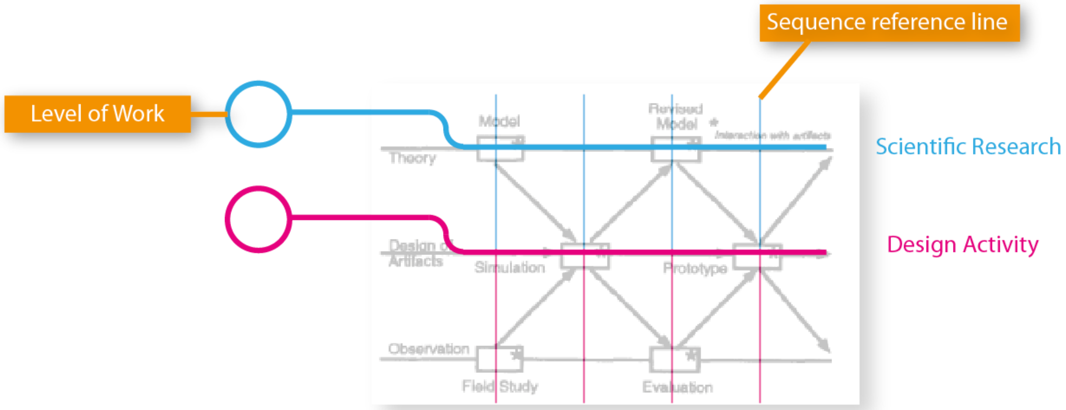


Diagram 7.2 *Collaboration matrix - initial overlay of levels of work and sequential reference line*

The split of the scientific research process into levels of work was based on the dimensions of scientific research identified in Chapter 5: The Social and the Rational. Additional to these levels that encompass activities exclusive to scientific research, a level was added to represent those activities that are not necessarily associated with the practice of science but with its commercialisation. The addition of this level was deemed necessary since it seems that at least for most of the scientists who took part in the case studies, being involved in the pursuit of commercialisation is potentially a natural progression of their research. The level of commercialisation (included as part of the scientists' activities) was developed from a number of informal interviews with officers from UTTO and scientists. On the other hand, the design split in levels was directly drawn from the design team's recollection of the design process undertaken during all case studies. This design process included three main levels: first, the definition of the project aim and of an initial design task; secondly, the design development; and finally, the project's conclusion.

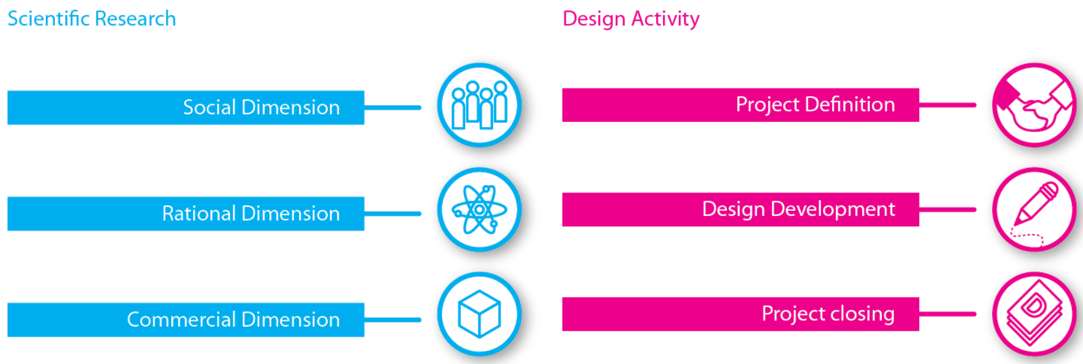


Diagram 7.3 *Levels of scientific and design activity for the collaboration matrix*

Subsequently, with the purpose of making easier and clearer the mapping of designers' and scientists' activities, each of the levels was subdivided into activity headlines, in order to map specific inherent activities.

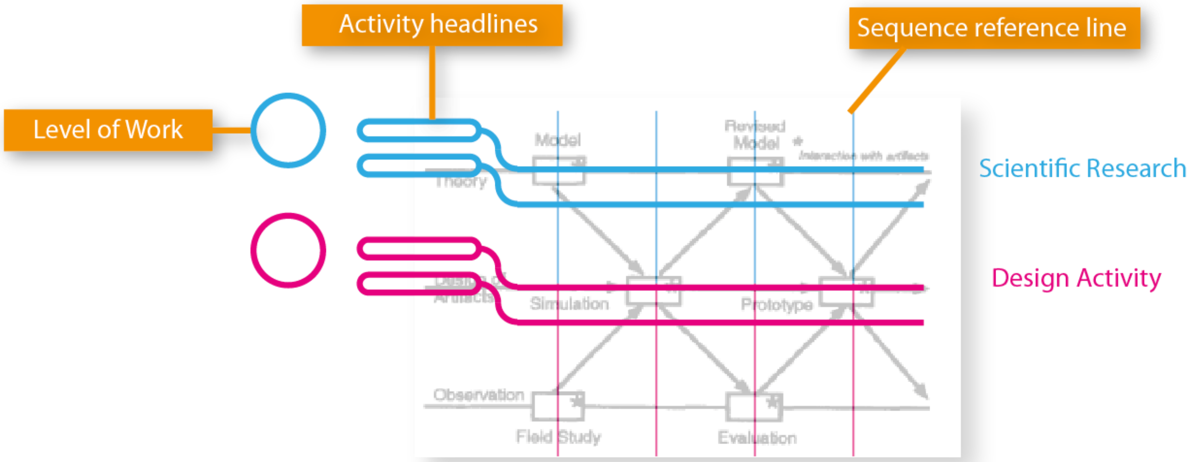


Diagram 7.4 *Levels of work are divided in activities in the collaboration matrix*

These activities were drawn also also from Chapter 5's explanations of the nature of scientific research. These activity headlines were next subdivided into activity stages, to help map activities within their own specific stages.

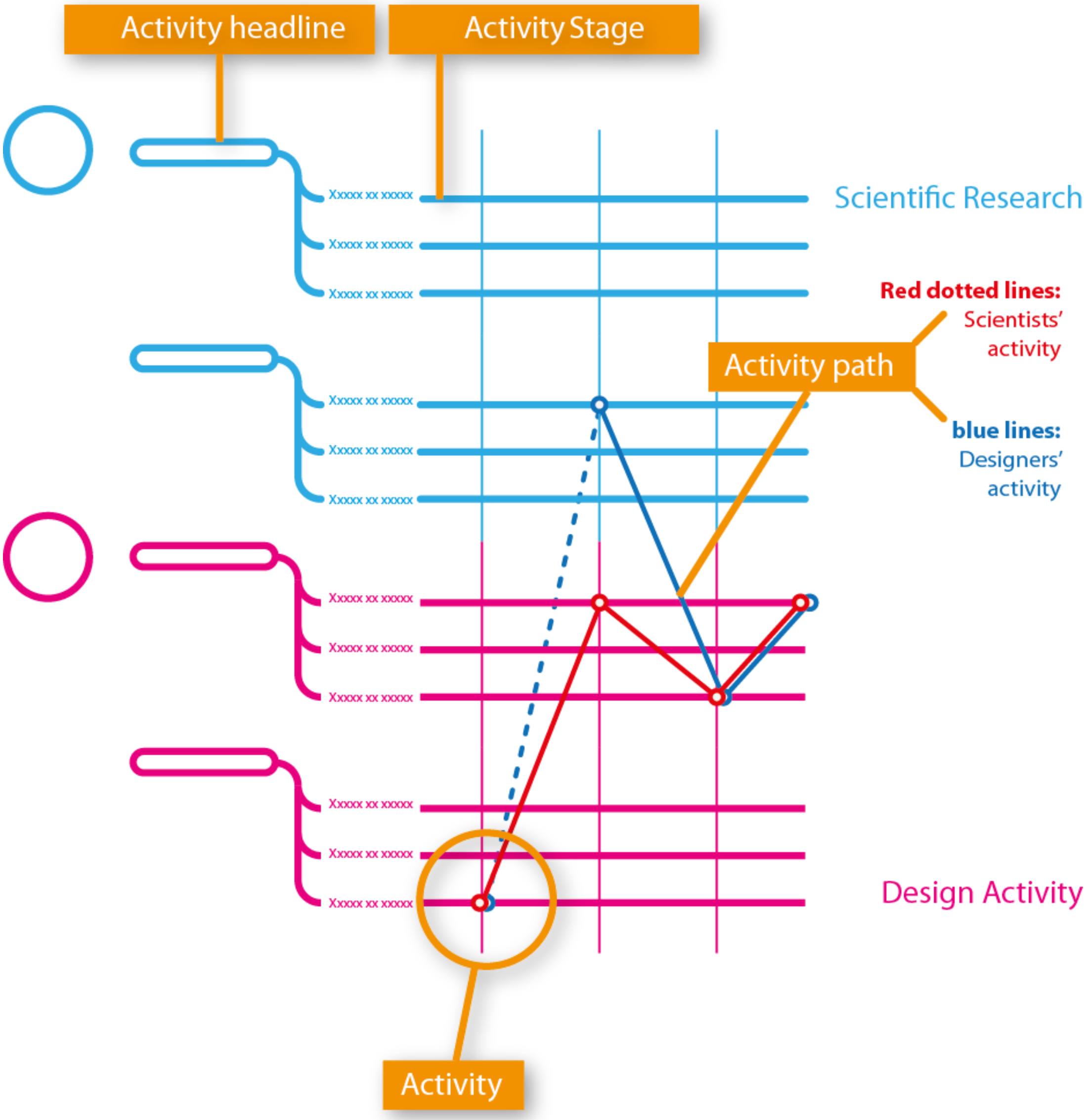


Diagram 7.5 *Activity headlines are subdivided in activity stages. Activity is mapped with small circles and lines (activity path). Red lines correspond to scientists' and blue to designer's activity.*

This way of subdividing the different activities related to scientific research was shown to the scientists during interviews after the collaboration projects ended, to verify its accuracy and its comprehensiveness. All of them found it comprehensive, but suggested some minor changes and additions which were included in the final version of the collaboration matrix. Amongst these changes were the inclusion of IPR and Patent application, and the addition of Hypothesis Generation as a subheading for Theory Development and Hypothesis Testing as a subheading of Experiments. Diagram 7.6 corresponds to the collaboration matrix format that was utilised to map all case studies.

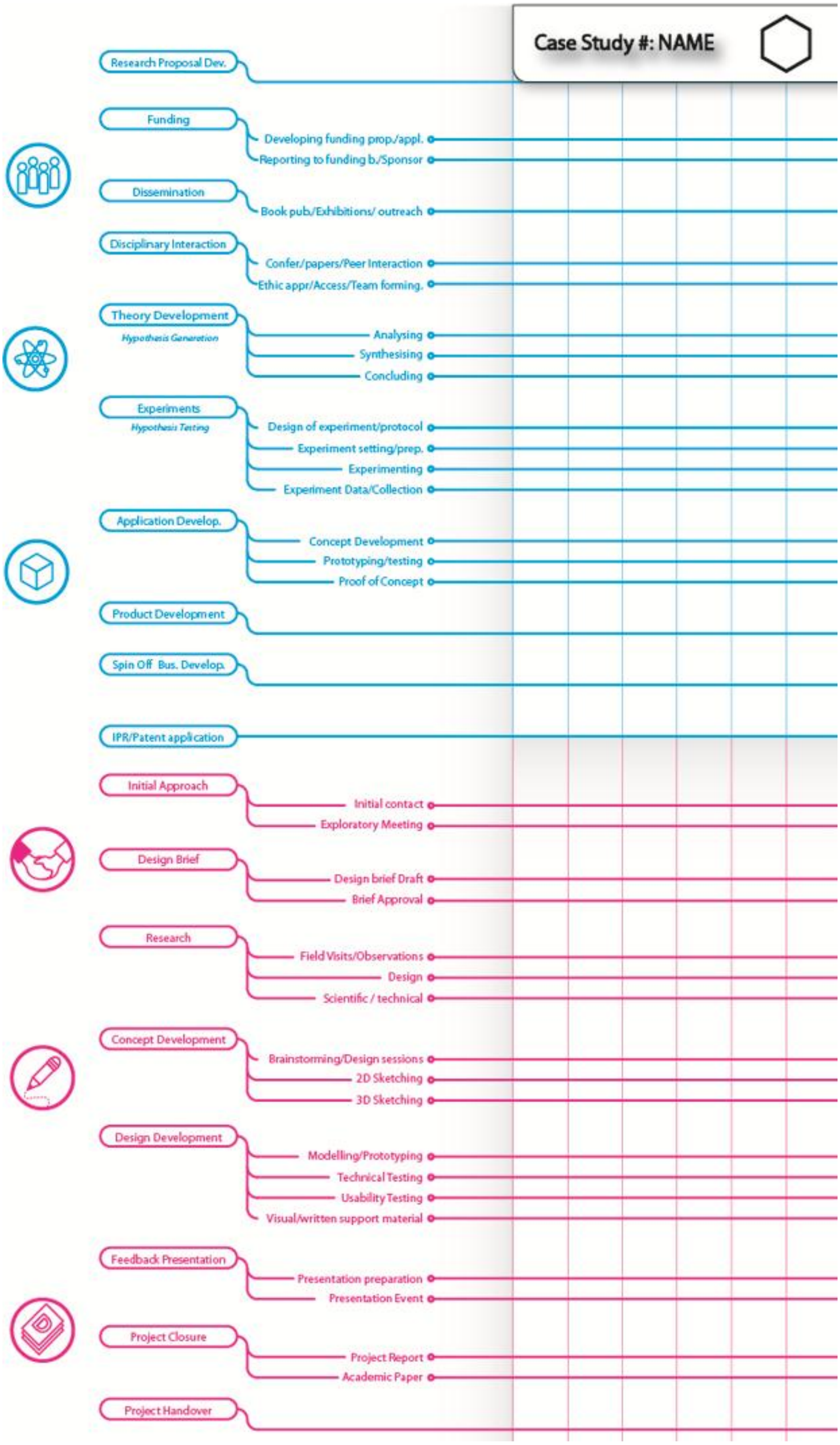


***Diagram 7.6** The collaboration matrix format utilised to map all case studies*

In the following sections of this chapter, an account of the 3 exploratory and 2 development case studies will be presented.

- **Exploratory Case Studies**

  Case Study 1: Mask for Respiratory Therapy

  Case Study 2: Fluid Handling System for Immunoassays

  Case Study 3: Wearable Application of a Multistable Material

- **Development Case Studies**

  Case 4 Communication tool for Stem Cell researchers

  Case 5 Imagining the future of Biophotovoltaics

For each case study, there will be an introductory explanation of the collaboration context explaining the motivation of the scientists and the designers to be engaged in collaboration, and an illustration of the issues (or lack of them) to be addressed by the design team. This will be followed by a collaboration matrix with the collaboration mapped on it and an explanation of i) the collaboration process, illustrating how the collaboration started, and ii) the design process, describing how the collaboration developed. Each case study explanation will conclude with a description of the collaboration outcomes.

7.4 Case Study 1: Mask for Respiratory Therapy

While conducting research on gas delivery to patients with respiratory problems, a researcher perceived the need for a mask for the administration of gases in a controlled manner when conducting tests with his patients. For this, the scientist examined several existing masks looking for the one that would provide perfect sealing on patients' faces. After carrying out several trials and tests, he found that the masks available on the market did not provide effective sealing or were not sufficiently comfortable for the patients over lengthy periods of study.

Picture 7.1 *The scientist testing his mask's prototype (Mask distorted to protect IPR)*

To address this problem the scientist designed a mask that would provide the required sealing, based on a sealing principle he devised and using materials readily available at home. The researcher developed several models and finally built a prototype of the mask which he then tested on himself, obtaining almost 100% sealing (Picture 7.1).

At the same time, while examining existing masks and developing his own, the scientist also realised that a mask based on his sealing concept would have commercial potential in medical research, and in clinical and therapeutic markets.

At this stage the scientist was faced two main challenges: on the one hand, to be able to develop his mask to the point at which it could be used for testing his gas delivery research on real patients; and on the other, to subsequently develop his mask as a marketable product.

However, the scientist realised that his prototype was inadequate: it was not made of materials suitable for a clinical environment and medical trials, it was not designed in a way that enabled production of a standardised small batch (for clinical trials), and it was not comfortable enough to try on patients. Consequently, he would not be able to conduct his research experiments or to undertake the necessary medical trials to transform his idea into a commercial product. At this stage, the scientist thought of having professional design input. He stated that when he "*got to something which worked and … thought* *it wasn't too ridiculous*", he thought of finding "*somebody who had proper design skills*" (interview before presentation, min. 08:50 on the recording).

At this point, the scientist contacted the university technology transfer office (UTTO) seeking help to develop his idea at the required level. Specifically, he was looking to have his concept developed into a mask that could be tested on users. He was interested in finding materials that would make the mask comfortable to wear, and that allowed the manufacture of a batch of 30 masks for use in clinical trials and experimentation. He hoped that this would lead to the development and improvement of oxygen therapy techniques and accurate gas measurement. He was also seeking to use them as the basis for the development of a mass produced mask, to target the medical research market in the first instance, and then the clinical and therapeutic market.

7.4.1 The Collaboration Process

After being contacted by the university technology transfer office, the design team attended an initial meeting with the scientists and members of the UTTO (point 1 on the map, p.23). In this preliminary meeting, the design team agreed to produce a working design brief so all project stakeholders could discuss and agree on the project programme, its tasks, objectives and deliverables. The brief also would help to ensure that the designers had a clear understanding of the project design parameters and the mask's potential primary and secondary users (patients and clinicians) and context characteristics (labs and hospital wards). At this stage, while a collaboration agreement was tacitly accepted by all participants in principle, internally the design team further discussed the suitability of the project as a case study, because of doubts on two aspects. First, the main concept of the mask seemed to be quite developed as an idea, so the design task appeared to be limited to finding materials and ergonomic adaptation. The design team was concerned that the project seemed to be too similar to those that would frame a normal product design consultancy commission. Rather than being involved in the scientific research process, the designers felt that they might be solving a standard product design problem in which the customer happens to be a scientist.

However on further consideration, the project appeared to provide an opportunity to understand what the impact of a “normal product design project” would have in scientific research. In addition, the project would provide a good opportunity to demonstrate to the gatekeepers (UTTO) the design team’s capabilities. Finally, as the design team had been recently formed, this project would be “safe” enough to allow team members to develop working and collaborative practices.

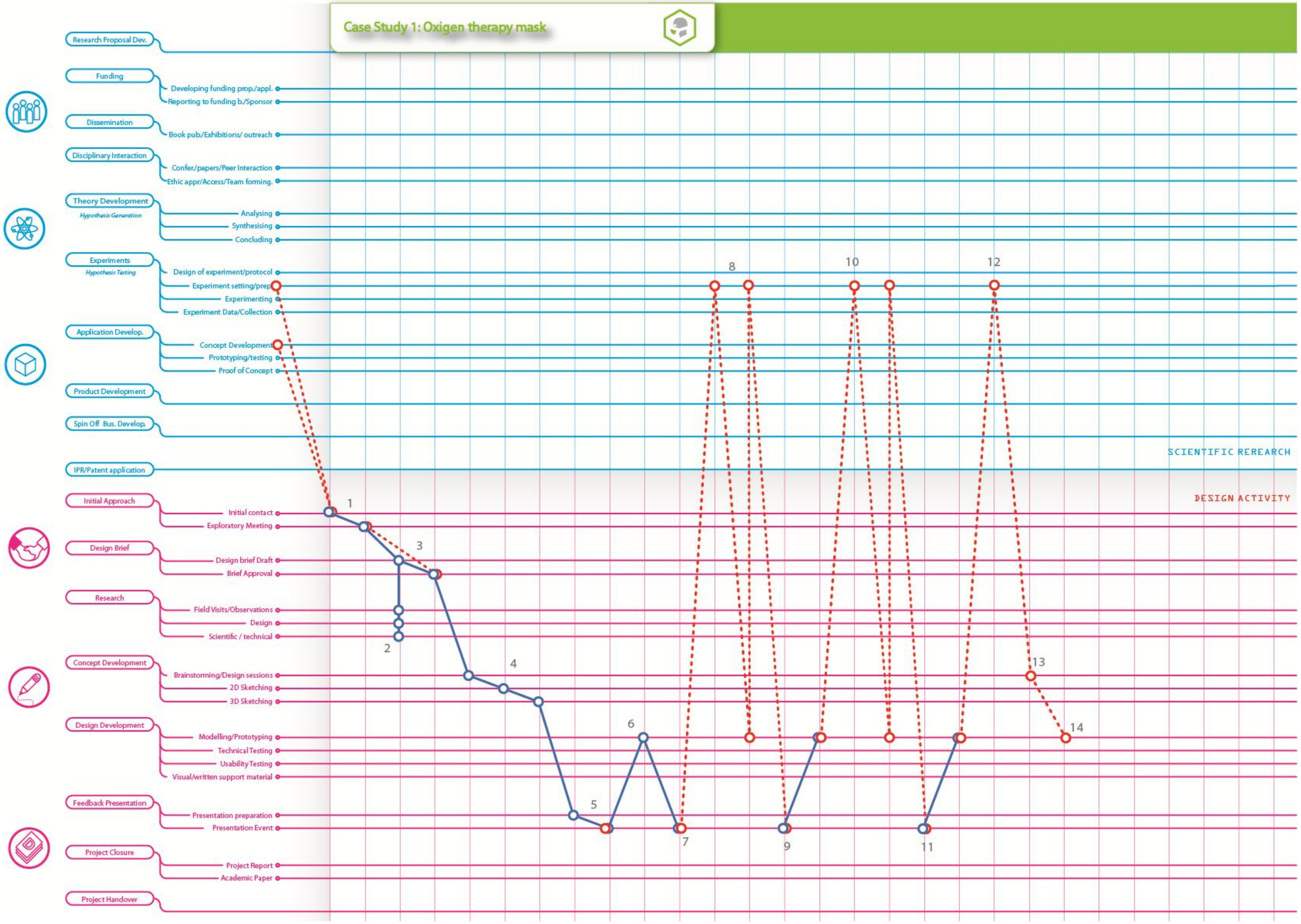


Diagram 7.7 *Mapping of Mask project on the collaboration matrix*

7.4.2 The Design Process

Following this initial meeting, the design team conducted a guided visit to the hospital in order to observe patients with different levels of respiratory problems (point 2 on the map). The designers felt it necessary to directly observe patients in their environment, and to be able to revisit the information received in the field. After observing patients, the team looked at different types of commercially available masks, discussing their characteristics in comparison to the scientist's concept. On the same day, a first draft of the brief was presented including a detailed work programme and product specification, a description of who would be using the device and the context in which the product would be used (point 3 on the map).

Picture 7.2 *The scientists, UTTO officers and the designer trying existing commercial models of gas masks during a visit to the hospital*

The brief was approved in principle and it was agreed that the design team would focus on developing a mask for clinical trials and experimentation (leaving the potential development of a mask for commercial purposes aside for a later development). The focus on trials and experimentation meant that the project was no longer primarily concerned with exploitation.

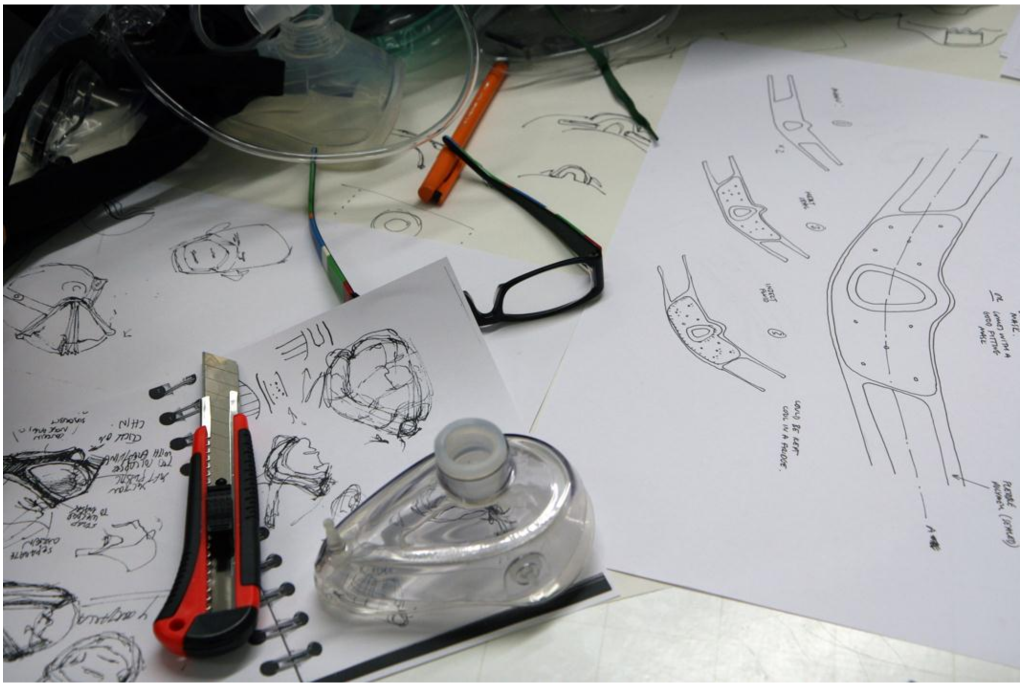
However, the design team still did not have a complete idea of the mask's possible scenarios of use, and requested the scientist to produce a list of the mask's potential applications. Additionally, even though the development of the mask for commercial purposes had been put aside for later development, the design team asked the scientist to estimate the size of the potential market for the mask. This request compelled the scientist to reflect on the mask's possible contexts of use and to think of it as a commercial product, writing down his thoughts on this. In this way, the scientist revealed tacit information about the mask, producing an additional list of the mask's possible ways/scenarios of use.

This list was developed by the scientist together with an explanation about compliance with material and product standards for hospitals, and a projection of the mask's market potential. This new information uncovered new design requirements for the mask and led to a further modification of the design brief.

Following the scientist's clarifications, the design team carried out a brainstorm session involving other designers. At this stage the design team was not sure that the scientist's sealing concept was the best possible solution (point 4 on the map). For this reason, the task for this brainstorm session was to generate designs of masks based on different sealing concepts. The brainstorm produced a variety of interesting alternatives, but none of them seemed to be substantially better than the scientist's, so the design team decided to follow the main principles of his original idea as they were understood at the time, but to explore new materials.

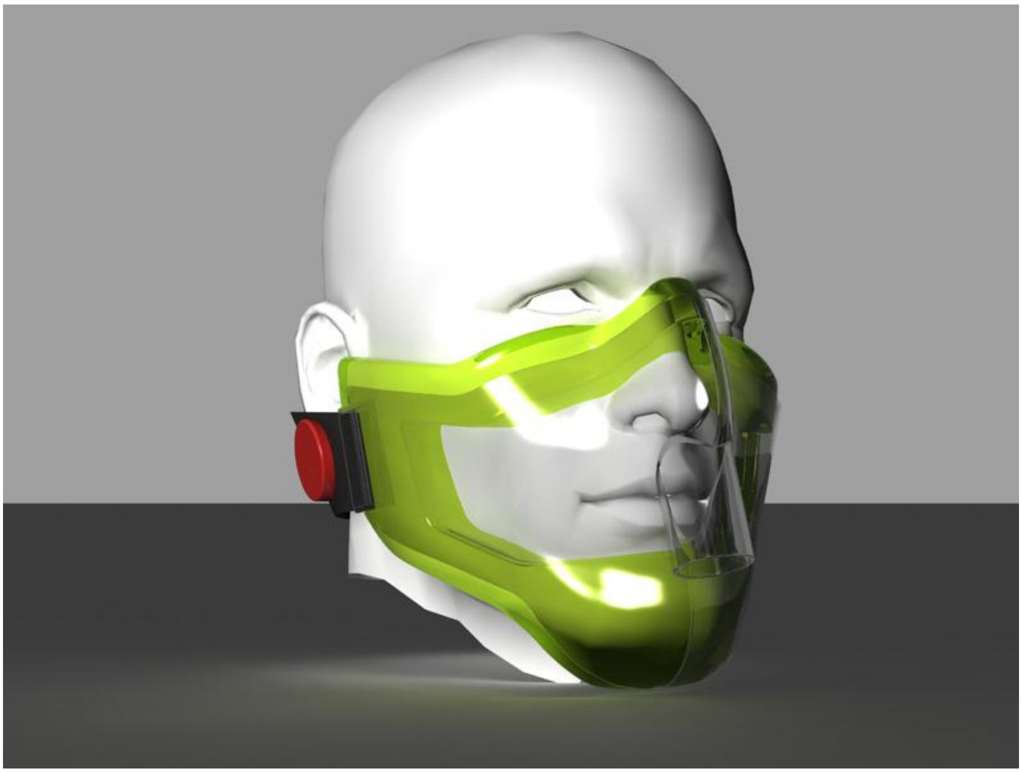
Picture 7.3 *Mask project brainstorm session*

The design team then proceeded to look at suitable materials and to produce sketches and models. This resulted in a concept for a mask that looked significantly different to the one developed by the scientist, but was based on the sealing principle developed by the scientist and promised to meet all the criteria of the design brief. Additionally, this new design made some of the features of the scientist's original concept redundant. The design team also decided to develop a detailed computer model. This would not have been necessary in other circumstances, but the designers felt that they need to make a case for their design proposal, since it departed somewhat from the scientist's original idea.



Picture 7.4 *Initial designers' sketches for the mask*

Picture 7.5 *An initial sketch model to test mask potential sealing principle*



Picture 7.6 *Rendering of the designers' mask proposal*

The designers and the scientist met again to look at the new design proposal (point 5 on the map). Although the scientist's reaction to the new design was positive and he eventually gave his approval to proceed with the construction of a prototype, he brought up for discussion some discarded features of his original design. Since the designers' proposal was very different from the scientist's initial prototype, having fewer components and a more streamlined shape, the scientists seemed not completely convinced by the new design and was worried that it would not provide as good a sealing as his original prototype did. However it was also clear that this could be proved or disproved only by testing it. At the end of the meeting the project team reached a consensus on the need to manufacture a prototype to see the effectiveness of the new design. Reflecting on this, the scientist said at the end of the meeting "*we've got to start somewhere*" (concept presentation interview, min. 01:06).

Picture 7.7 *Designers presenting their mask proposal*

The designers proceeded to build a prototype of the mask (point 6 on the map). The designers developed a computer model of it and went through several moulding steps until a testable mask was manufactured. Given the unique shape of the mask, it was not possible for the designers to make sketch models before the prototype was manufactured. This was an unavoidable risk, and the designers had to do their best effort to pre-empt all possible issues only using the mask computer model on a digital model of a human head. Once finished, the design team presented it to the project team (point 7 on the map).

Picture 7.8 *Designer finishing a CNC machined mould for the mask prototype*

Before the presentation, the scientist was interviewed with the purpose of understanding his expectations regarding the designers' work. He made it clear that with the designers' intervention he was hoping to have a mask that "*worked*" and was "*marketable*" (pre-interview, about min. 05.00). Although the scientist believed that the involvement of designers could potentially help to develop the mask saying "*if you put* *your mind to it and involve the right people, then potentially one can be developed*", he was also cautious and kept expectations low. He said "*I can even expect that we will actually be successful*" and added *"I think it is a very difficult problem…and one has to ask why hasn't somebody done it before…there is not a perfect mask*" (pre-interview, min. 22:07).

During the presentation, the prototype of the mask was presented to the scientist by the designers, explaining its main features and advantages, illustrating the design criteria utilised and describing its manufacturing process. The scientist tried the prototype on himself and it became evident that it met the design parameters regarding comfort, manufacturability and appearance, but most importantly it did provide a good sealing. However, during the presentation, the scientist expressed some concerns about certain features of the mask (e.g. strapping, chin sealing, etc.) Nonetheless, the group agreed that the importance of these problems (and their solution) would only become evident by testing the mask on a sample of people with different facial features. Although the designers had included a testing programme for the prototype, obtaining access to patients was difficult as the process of clinical consent and ethical approval is lengthy and complicated. For this reason, it was agreed that the scientist would carry out formal tests on his own with a sample of healthy people with different face shapes (and, later, on cadavers). However, the designers did not specify the criteria for conducting such tests and left it to the scientist to set them.

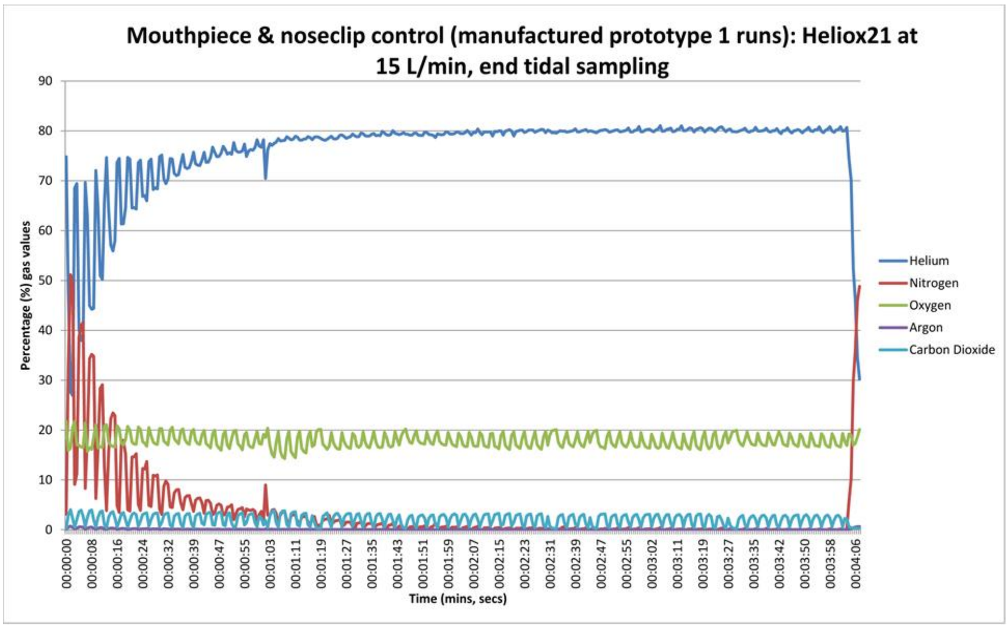
One of the designers told the scientist to *"go away and note down observations"* (presentation, min. 32:18).

Picture 7.9 *The scientist trying the designers' mask prototype*

After the meeting the scientist conducted some tests on a group of his colleagues at the hospital, and presented some readings from a gas reading device to the designers, reporting that the new mask satisfied the technical sealing requirements. However, little was reported on other important design aspects such as comfort, feeling, aesthetics, etc. (number 8 on the map) While completing the testing, the scientist made several amendments to the prototype to improve the sealing. This included modifications of the strapping system, and the addition of a functional sealing feature made out of a new material. The visual appearance of the prototype after these modifications was spoiled, as well as its manufacturing quality, so the design team decided to make a new strapping mechanism based on the straps that came with a pre-existing mask (number 9 on the map).

Picture 7.10 *Mask prototype modified by the scientist*

When further testing was carried out by the scientist on cadavers using the prototype with the new strapping system, some minor problems of sealing were observed. These problems were associated by the scientist with the vertical position of the cadavers and with their different facial anatomy (due to the lack of soft tissue under their skin). It is worth noting that the designers were not present while these tests were conducted and that they did not have the opportunity of observing these problems directly (number 10 on the map).



Picture 7.11 *Mask testing result, showing good (but not perfect) levels of sealing*

At this point, the scientist decided to modify the prototype using the materials and the sealing principle he had devised in the first place. On this occasion though, the scientist had a better understanding of it thanks to the tests he had carried with the designers' prototype and to discussions with the designers. The scientists tested the modified prototype with good results in terms of sealing, but it had lost most of the features of the designers' proposal in terms of comfort, aesthetics, etc. At this point the design team was not in a position to defend or continue with their original concept (based on the evidence from the scientist's tests) and decided to incorporate the ideas from both the scientist's and the design team's prototypes (number 11 on the map) but mainly based on their better understanding of the original sealing principle and materials suggested by the scientist. This was the last prototype iteration made by the designers, since the deadline for the case study had already elapsed.

After the designers produced this last prototype, the scientist took it for trial and this time the technical test was not as successful as it was in previous versions of the mask (number 12 on the map). The scientist decided to put aside all concepts tried so far, and developed and tried a new sealing principle for his mask, inspired on some of the ideas discussed during the collaboration meetings (numbers 13 and 14 on the map). However, the design team was not able to follow this new concept since by then the scientist had accepted a job in another university and the project came to an end.

7.4.3 Collaboration Output/Outcome

The collaboration output was varied. First, several sealing principles were developed and tested, creating potentially useful knowledge for further development of a respiratory mask. Also, a better understanding of the scientist's original idea/working principle was achieved. In addition, several mask configurations were tried and tested, creating useful knowledge for further potential design development. Secondly, the designers made the mask design requirements explicit, evidencing design requirements for the mask as a commercial product and as an experimental device. Thirdly, some possible scenarios for use became explicit during interaction between designers and the scientist, evidencing the mask's commercial potential.

7.5 Case Study 2: Fluid Handling System for Immunoassays

A team of biological chemists researching drug diagnostics ideated and built a fluid handling device based on a commercially available plastic component termed Micro Capillary Film (MCF) developed within their department and produced to order by a partner manufacturer. The MCF is an extruded array of parallel micro capillaries made out of polymer.

The idea for the device came "accidentally" while they were trying to use the MCF as part of a device for purifying proteins. They realised that a device incorporating the MCF could form the basis for a safer, cheaper and faster method of performing an immunoassay (a common laboratory test) than other existing and standard techniques.

Their device was built by adapting and assembling readily available parts from their laboratory. With this device, they were able to test and prove a novel working principle for conducting immunoassays. Also, they used it as the basis to outline an initial design specification for an improved version.

Picture 7.12 *Device developed by the scientists from parts found in their lab*

However, the device was not easy to handle, it did not allow multiple tests to be performed on different samples simultaneously, and it did not fit other standard components for carrying out immunoassays (microtiter plates, multiple channel pipettors, etc). As a consequence, it was problematic to develop a fast method of conducting immunoassays using the device. This made it difficult for the scientists to prove their idea by making a reliable and credible comparison with other existing immunoassay techniques.

As a result, the scientists were looking for the development and fabrication of an improved version of their handling device so they could:

- develop the new immunoassay procedure to reach the maximum standards of safety and reliability, while minimising the procedure time
- measure its levels of safety and reliability, its cost and its speed, so a comparison could be made with other existing competing procedures.

They were also interested in the commercial potential of their idea and were looking to have the main underlining design principles ready for the development of a commercial version in the near future and for a fully automated version in the long term.

The scientists were aware that they did not have the skills to design and manufacture a device to perform such a test and because of this, they approached the UTTO for assistance. The technology transfer office suggested that carrying out a comparison with competing technologies was also fundamental to convincing prospective investors of the device's potential. For this reason they suggested the scientists would need to engage with a designer to move the project forward. The UTTO subsequently organised a meeting with the design team working on the Design in Science project.

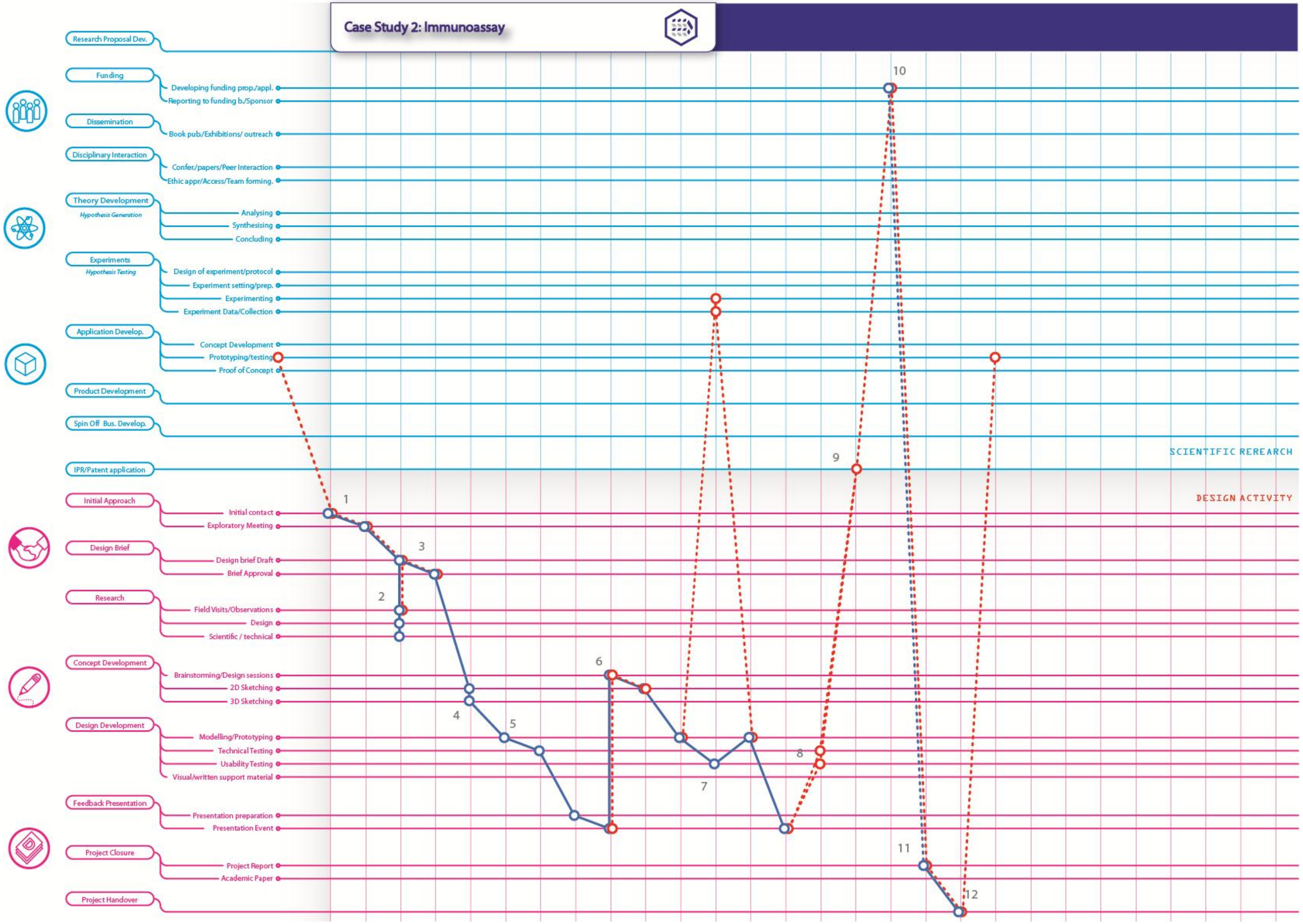


Diagram 7.8 *Mapping of Immunoassay project on the collaboration matrix*

7.5.1 The Collaboration Process

In the first meeting of the project team, the designers were given an explanation of the fluid handling device and were introduced to the general principles of immunoassays. The scientists demonstrated the device. They also presented a document comparing their device with competing technologies in relation to cost, time and ease of use amongst other factors (number 1 on the map).

Picture 7.13 *Scientists explain to the design team the principles of the fluid handling device and the general principles of immunoassays*

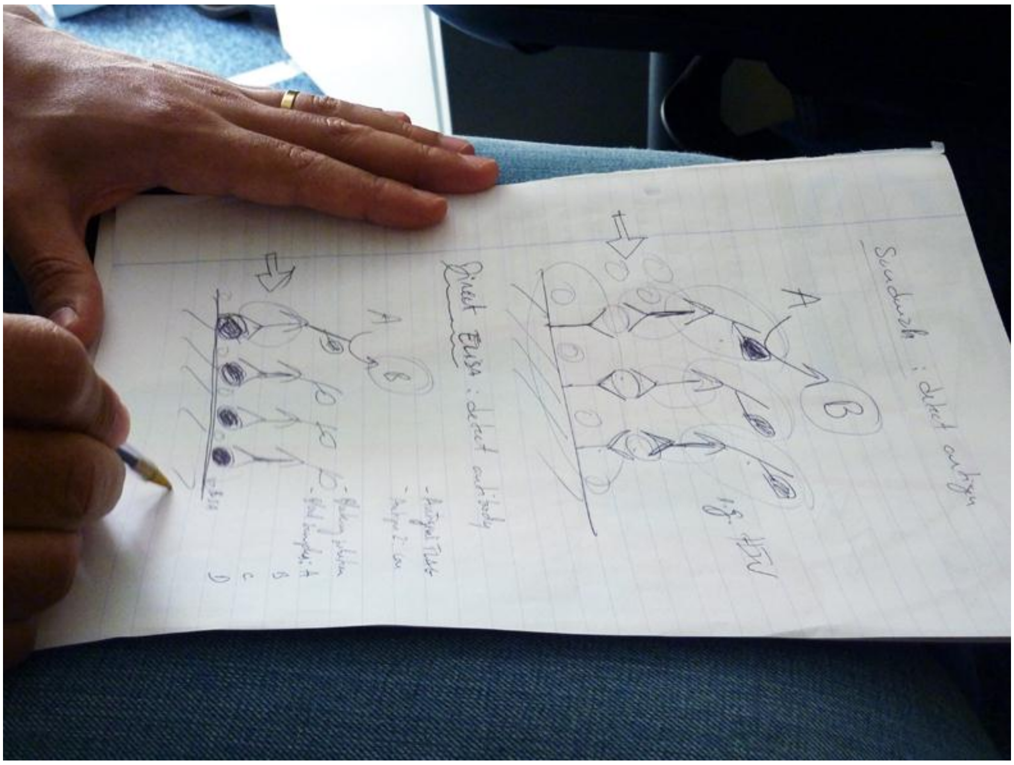
However, conducting an immunoassay in practice is a lengthy process that involves several steps, so a number of these steps had to be skipped. Also, a number of key aspects of the process were not directly observable, so they had to be explained using scientific terms. As the designers were unfamiliar with the immunoassay process, did not possess some fundamental scientific knowledge and were unfamiliar with the scientific terminology, the scientists had to go through a lengthy explanation.

However the designers felt that their understanding of the process and the context in which it happens was not sufficient to start thinking of design concepts. Subsequently they asked for an observation day so they could have a real sense of the immunoassay process, and be able to identify the theoretical aspects of the process with the actual stages of it (number 2 on the map).

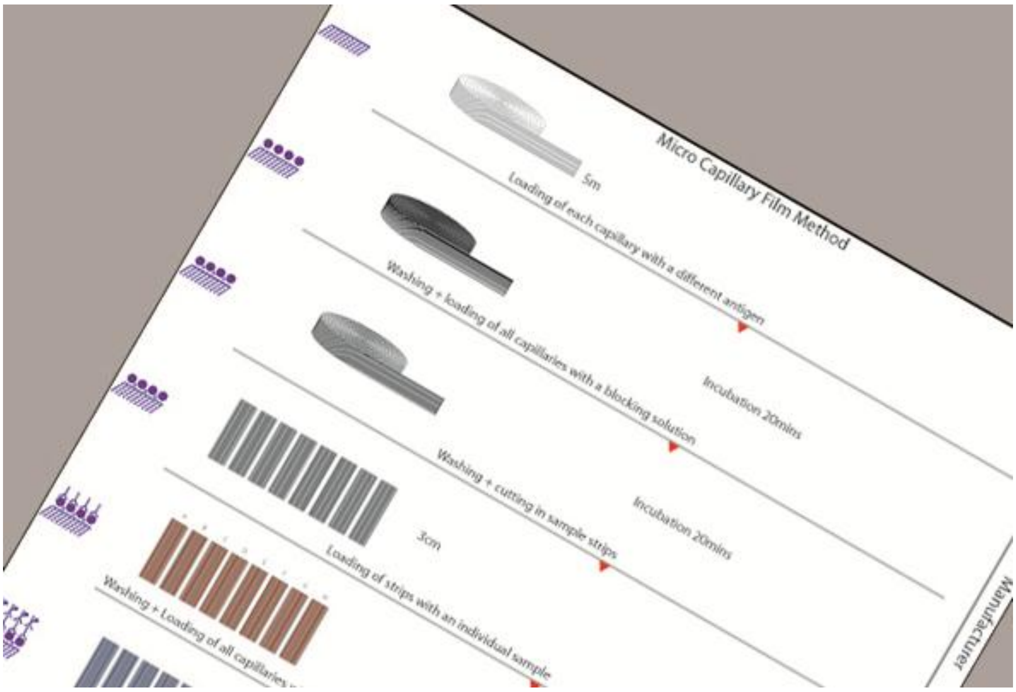
The observation day was carried out and helped the designers to fully understand all the steps and the main scientific principles of the standard procedure and the procedure enabled by the MCF. The scientists conducted a full immunoassay test and invited the designers to participate, encouraging them to use the tools and reproduce some of the procedures of the process. The designers recorded the procedures, using notes, sketches, pictures and video. They noticed issues related to the use of the device such as comfort and error control. They also observed potential problems of safety such as contamination of samples or undesired researcher’s contact with samples. The designers examined the compatibility of the system with other laboratory equipment and with the surfaces and environmental laboratory conditions such as lighting, surface availability, and storage space amongst others.

Picture 7.14 *A designer and a scientist during observation day*

Also, a diagram prepared by the scientists with scientific symbols was used during the day to explain those aspects of the process that were not directly observable. This diagram became a reference tool for the designers to follow up the process and to understand what the objective of each stage was and how it related to the whole process. Some days later, the designers created their own diagram of the process, assigning a pictogram to each stage of the immunoassay, identifying its name and its corresponding scientific symbol. The designers also prepared a design brief, outlining the project background and its aim, specifying the desired characteristics of the device and a work programme. The brief also included the designers' version of the process through their diagrams (number 3 on the map).



Picture 7.15 *Scientists explanatory drawings*



Picture 7.16 *Diagram of the immunoassay process created by the designers*

The brief was approved by the scientists and confirmed that the designers had achieved a good understanding of the process and its associated scientific concepts. In an email one of the scientists wrote, *"You've clearly captured every single relevant aspect of immunoassay technique during the demonstration! Your pictures and drawings look brilliant and that's all I have to say for now"*.

Although at the beginning of the project, the design team was not familiar with the scientific concepts and vocabulary related to immunoassays, this mix of observation, scientific explanation and visualisation of the process through diagrams, helped to establish effective communication between scientists and designers. It was apparent that the designers were able to adopt the scientific terminology without resorting to metaphors or simpler vocabulary.

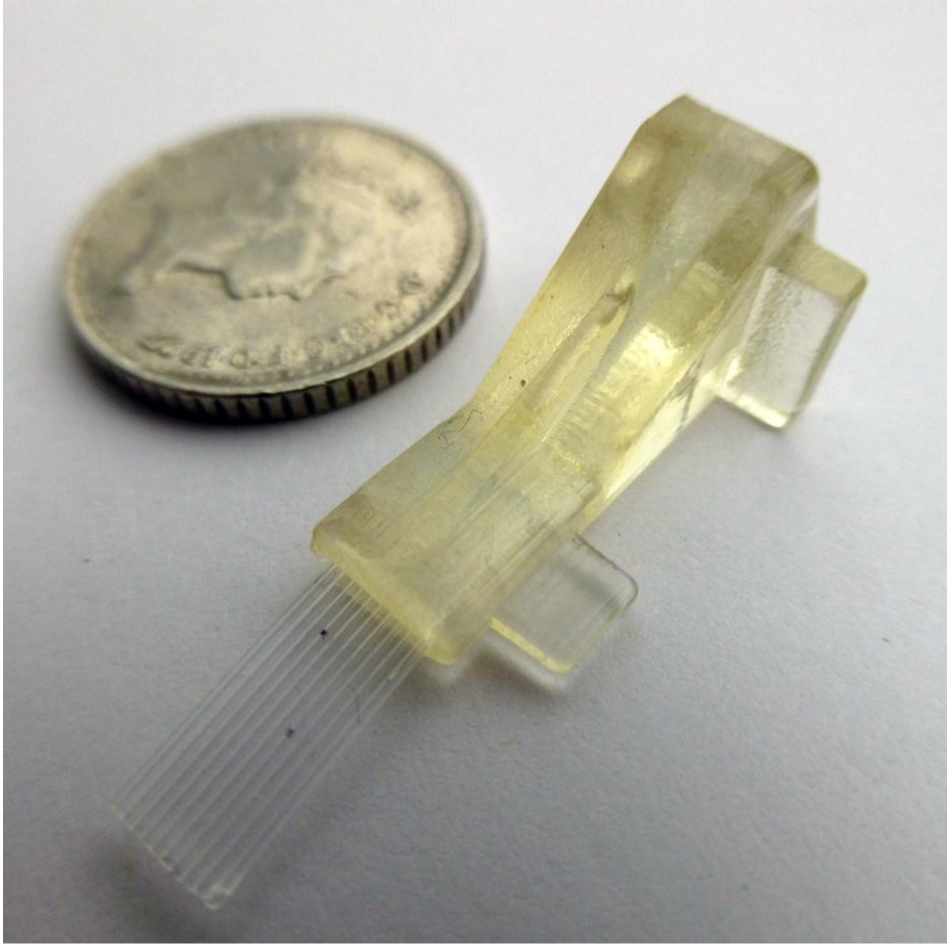
7.5.2 The Design Process

The design team started their design process by borrowing some standard equipment used to carry out immunoassays. They intended to use these in combination with sketch models to develop some initial design concepts (point 4 on the map). The design team soon realised that any idea they might develop should be proved beforehand to be as efficient at handling liquids as the model developed by the scientists. It was crucial that any concept presented by the designers guaranteed perfect control and sealing of the fluids. So the production of sketch models and function models become mandatory.

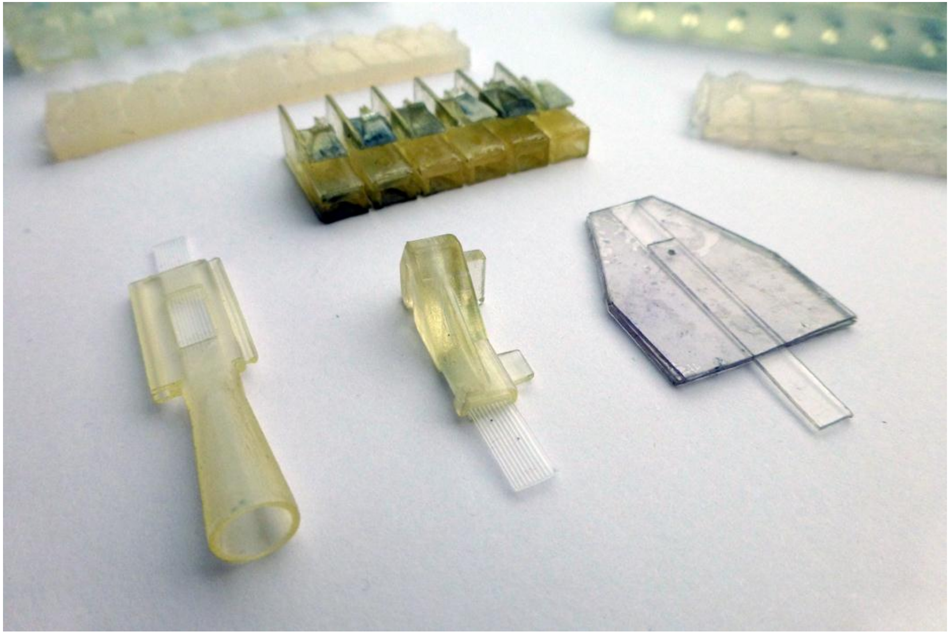
As there was a close relationship between the size of the components and the behaviour of the fluids, it was important to develop working testing models on a 1-to-1 scale. This was also essential because any design had to be compatible with the shapes of other complementary laboratory equipment such as pipettor nozzles.

The reduced size of the components and parts did not permit the designers to use the standard sketch modelling techniques they were used to. So they had to resort to computerised rapid prototyping techniques to create the sketch models (point 5 on the map). Since these techniques are considerably more expensive than normal sketch modelling techniques, the process of consultation with the scientists was more thorough and intensive than usual. Interestingly, the presentations of the models, carried out in the scientific labs, became almost “design sessions” where the scientists and designers considered different ideas and took key design decisions (number 6 on the map).

It was equally important that the designers developed competing ideas, and subjected them to scrutiny by the team. While explaining their concepts and models, the designers also presented visualizations of how the device would be used as part of an experimental kit. This helped the scientists to engage in the design process but also to define a key principle of the device's operation to guarantee the design's perfect technical performance.



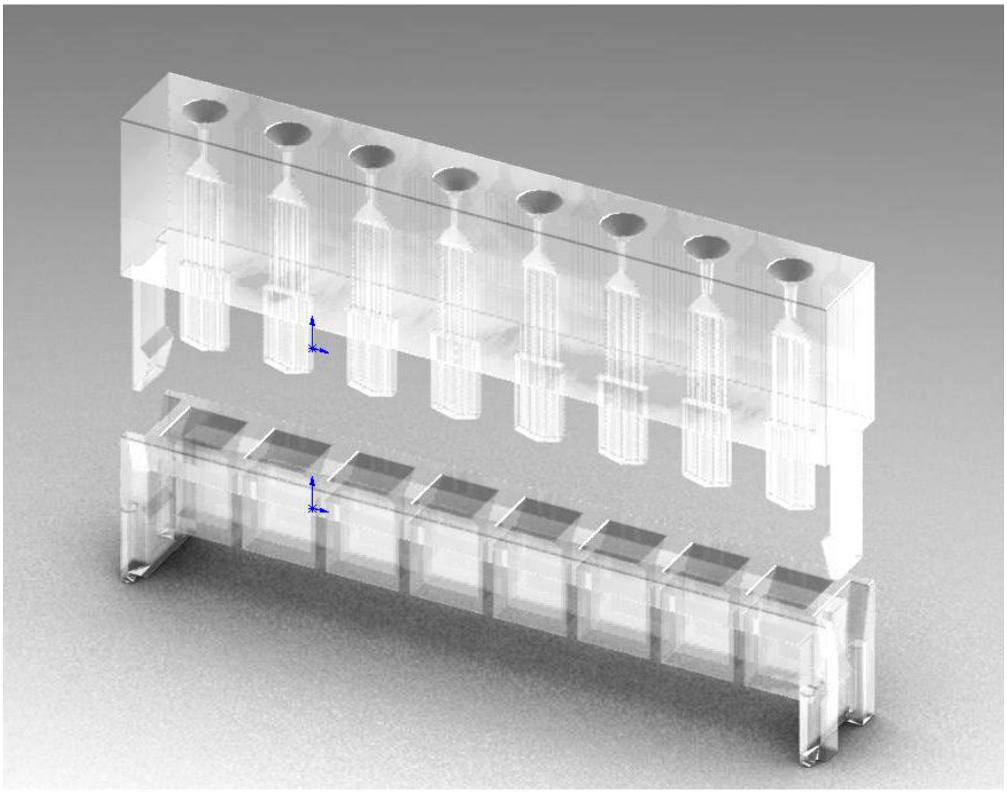
Picture 7.17 *Rapid prototyping sketch model of an immunoassay device*



Picture 7.18 *Various sketch models for immunoassay devices*

Most of the ideas presented by the designers were based on the scientists' original idea of using MCF. However, one of the designers' ideas excluded the utilisation of MCF. This idea was presented to the scientists and challenged the foundations of their original concept, encouraging them to examine it thoroughly, analysing the pros and cons of both versions. Eventually they produced a document proving that their idea was more suited to the currently available materials and production processes. In a post interview one of the scientists stated: *"...I remember when Carlos came out with this crazy idea in which you could, rather than attaching the films to the fluid handling device, build everything in one solid frame and he made us lose our pride, because that was personal, that would basically keep (us working on) our science rather to do without the need of, you know, without really go into our patent..." (*post-interview, min. 6:20)

After a few model iterations and a number of discussions with the project team, the design team proposed a final version in which a set of objects formed a fluid handling system (number 7 on the map). The system provided an adequate sealing for 8 strips of MCF integrating parts made of different materials and included three main components: the MCF, an MCF cassette and a sample/wash well. The system also defined some functional features, such as a modular system of assembling and stacking, which would be design principles for its further development as a marketable product.



Picture 7.19 *Computer-generated model of the designer's final proposal*

A prototype was made and the scientist carried out some tests to prove that the system successfully met the technical and design parameters (point 8 on the map). They also compared the system with existing competing technologies, and using this comparison in conjunction with material generated by the designers (sketches, diagrams, models and prototypes), applied for additional funding to continue with the development of the project (point 10 on the map). However, since at this stage their idea had become concrete enough to protect, they filed a patent application (number 9 on the map).

Picture 7.20 *Final prototype of the immunoassay handling system*

Their application was successful and they were granted sufficient funds to continue with the project for a further year, and to pay for external design support to develop and manufacture a batch of test prototypes for laboratory trials.

At that stage it was decided that the scientific team should bring in an external design team to continue with the project. In view of this, the current design team produced a design rationale document that included an explanation of the design, the procedure for use and useful information for additional design development (point 11 on the map). Additionally, the design team met the external design team for the project handover, handing them the design rational document and answering their questions about key design aspects (number 12 on the map).

Even though the main outcome from this collaboration related to the development of the immunoassay device, there was also an unexpected result. It seems that the scientists took note of the way in which the designers employ diagrams to synthesise and communicate their understanding of complex ideas, and started to apply it in their own work. In the collaboration post interview, one of the scientists intimated that he started to use similar diagrams to the designers' for their presentations to colleagues and especially to those without a scientific background. The scientists realised that by using this kind of diagram, other non-scientists would better understand their research and ideas. One scientist said: "*Actually you* (the designers) *gave us inspiration for, you know, for many different documents we prepared…*" (post-interview, min. 13:00)

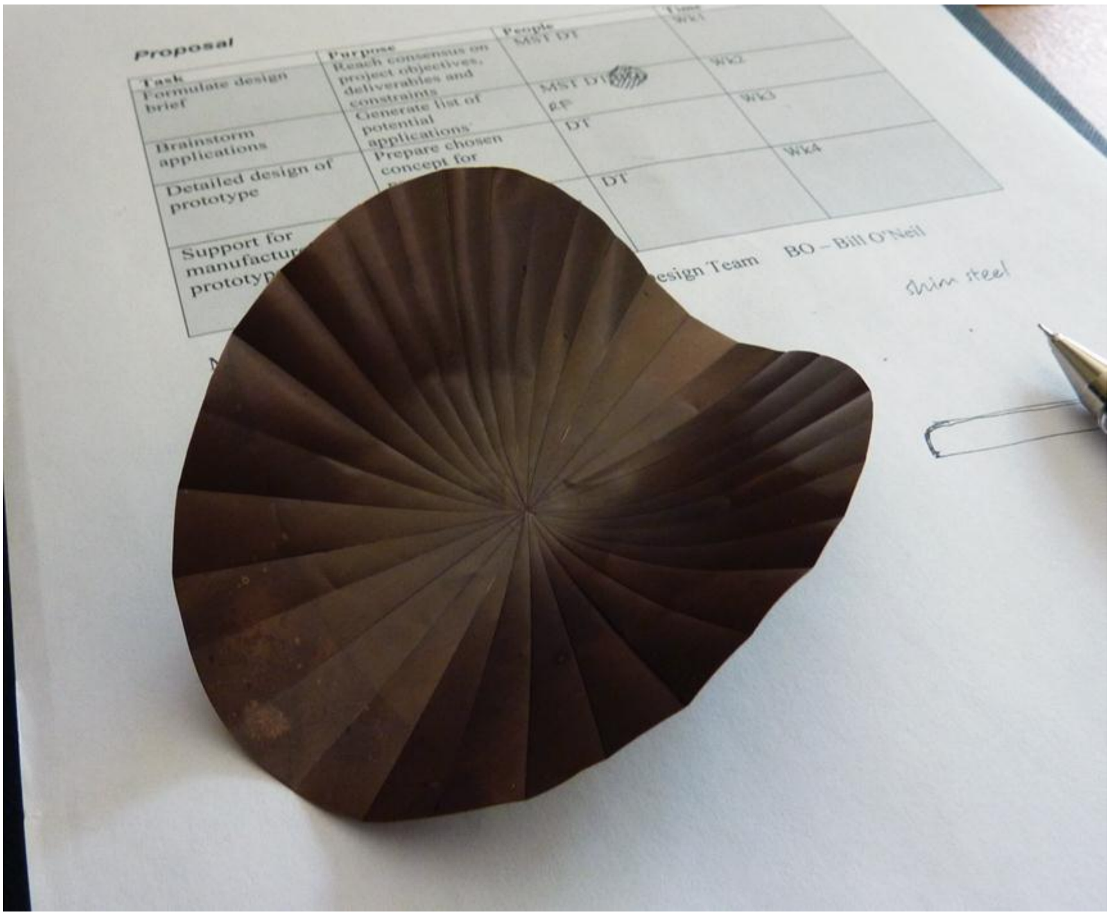
7.5.3 Collaboration Output/Outcome

The collaboration produced diverse outputs. First, it generated several possible new configurations for an immunoassay device using MCF. As a consequence of this there was an increased understanding of the working principles of MCF for immunoassay tests. The second output was a design specification for a suitable immunoassay device using MCF. The design input played a crucial role in applying for the scientific funding which was secured for further research and development of the immunoassay device. Finally, a less tangible output was the design-inspired graphic communication style adopted by scientists in presentations about their work.

7.6 Case Study 3: Wearable Application of a Multistable Material

A scientist developed a forming process for producing structures from metallic sheets that can be configured into a variety of preformed stable shapes that has been plastically formed (e.g. a flat metal sheet that can be rolled into a tube, or can be curved into stable opposite directions). These structures are named multistable structures. As part of this development, the scientist published his research on calculations explaining the behaviour of metallic sheets with induced multistable properties (through his forming process). He also produced a variety of different samples generated from variations of his forming process and by trying different types of materials.

Together with the UTTO, the scientist was looking to attract commercial partners interested in the development and application of this technology. To this end, the UTTO commissioned a marketing consultant to identify possible applications of multistable metallic materials and potential industrial partners. Additionally the UTTO help the scientist to protect the technology IP by filing a patent. Also, the scientist made a series of sketch models of potential products utilising multistable metal sheets produced in his lab.



Picture 7.21 *Sample of a multistable material made by the scientist*

The scientist and a UTTO officer used the samples and sketch models to show the potential of multistable materials to possible industrial partners and manufacturers. Although the manufacturers showed interest in multistable materials, the scientist realised that the industrialists would not invest in developing the multistable properties of their materials or products at such an early stage. Also, he was convinced that the development of working prototypes was necessary to attract the attention of potential partners: *"…We* *find that every time we tried to exploit this commercially we were coming out against the, I suppose, the difficulty of not having a prototype that suits a need of the market or the industry"* (post-interview, min. 17:45).

At some point one of the manufacturers took an interest in the possible use of a bistable[16] hinge prototyped by the scientist in one of his high range wearable accessories. Although the hinge seemed to work well, the manufacturer expressed concerns regarding its size, and asked if it was possible to have a more refined hinge of a smaller size. It became apparent to the scientist and the UTTO officer that developing such a hinge would help to consolidate collaboration with this accessories manufacturer.

They also believe that a smaller hinge would render possible the production of low-cost wearable accessories for people with limited purchasing power. This would potentially open new market opportunities for the interested manufacturer.

At this stage the scientist began to develop a bistable hinge of an appropriate size to be used in a wearable accessory. With the purpose of making its potential future production easier, it was also decided that the hinge should be seamlessly integrated into the body of the accessory. The scientist also decided to develop this new prototype using or adapting the instruments and equipment already available in his lab, in order to save time and resources. As

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[16] Bistable is a form of multistable material that changes from one shape to other as a consequence of a mechanical effort.

a secondary task, the scientist and the UTTO officer also wanted to explore and expand the range of possible applications for multistable structures.

As a consequence of this, the UTTO officer suggested involving designers in the project for both the development of the hinge and the exploration and expansion of multistable structures applications.

Picture 7.22 *Model of bistable hinge made by the scientists*

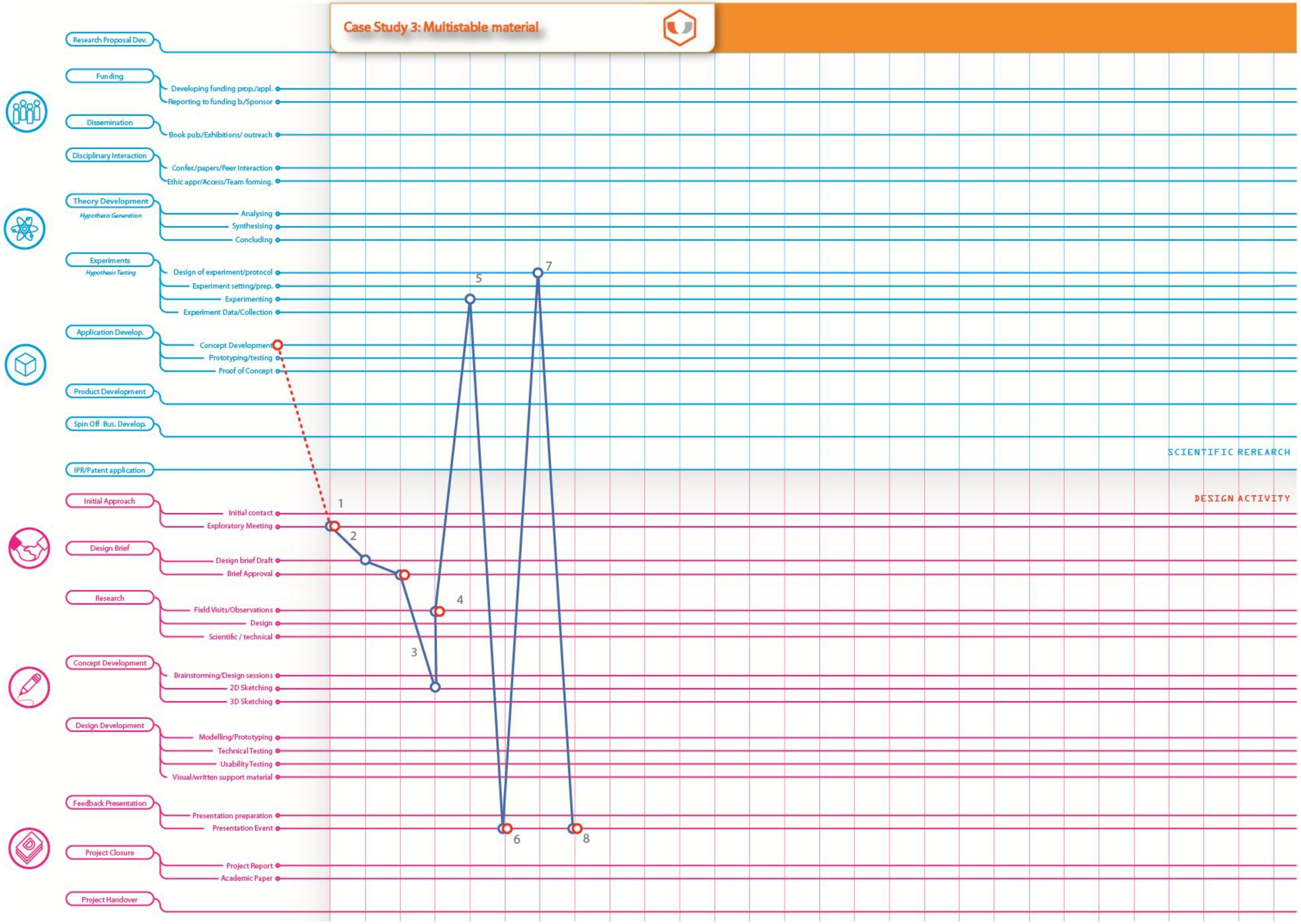

Diagram 7.9 *Mapping of Multistable project on the collaboration matrix*

7.6.1 The Collaboration Process

In the initial exploratory meeting of the project team, the scientist explained the principles of the method that he had developed to bring multistable properties to metallic sheets, and he showed some samples of multistable and bistable materials (number 1 on the map). The samples displayed a range of relatively small pieces of metallic sheet, all processed in different forms and showing either bistable or multistable properties. He also displayed a sketch of an electronic device with bistable properties, and of a wearable accessory with a bistable integrated hinge. During this meeting there were discussions related to the type of support that the designers could provide for the scientist. At that moment it became apparent that the scientist and the UTTO officer wanted designers to help create well-crafted prototypes of products using multistable materials, so they could attract more interest from potential industrial/commercial partners. They wanted to begin with the hinge application since it was perceived as the one application that would not require too much investment. It was thought that this development entailed not only the down scaling of their current hinge, but also the miniaturisation of the forming process and experimentation with different materials.

***Picture 7.23** The scientist explains the multistable forming process. There are samples of multistable materials on the table, as well as a multistable forming device*

Immediately after this first meeting, there were discussions amongst the research team about the suitability of this case in relation to the aims of the case studies. There were some doubts about undertaking it, since it seemed that the scientist's need (and the UTTO officers' need) for design input, was more focused on attracting commercial interest in his patented process than progressing with his research activities. The research team was concerned that the scientist wanted something that could not be delivered with the technology in its current state. Eventually, the designers thought that during the process of developing the hinge, questions would arise that might foster new thinking and a suitable development of the technology. On this basis, the team decided to engage in collaboration and soon afterwards they developed a design brief (number 2 on the map).

7.6.2 The Design Process

Following the approval of the design brief, the designers started to sketch some initial concepts for the hinge. Soon they realised that any shape or concept they wanted to propose needed to be demonstrated with models utilising the actual material. Using other modelling materials would not have been suitable to replicate the physical characteristics and behaviour of metal bi- or multistable materials. As a consequence, they wanted access to the material and to the tools to produce it, and to learn the multistable forming process in practice. Additionally, the designers were hoping that having access to the multistable forming process would allow them to introduce innovations into the process and to generate new and exciting types of multistable materials (number 3 on the map).

The scientist granted the designers access to the workshop in which the multistable samples had been made, so they could learn and practice the multistable forming process, and use multistable material for sketch modelling. He also offered to demonstrate how to operate the forming machines to produce multistable material (number 4 on the map). The design team was made aware that the main person (a PhD student) who had worked on the setting up of the laboratory and the tools, and who had developed most of the samples available, was not working with the project any longer. So the design team did not have access to valuable practical information on the forming process from that researcher.

Picture 7.24 *Scientist demonstrating the process of multistable material*

During this period of experimentation (number 5 on the map) it became clear to the designers that although the nature of multistable materials was well understood by the scientist, the process of formation of multistable material was not standardised, and the tools used for it did not allow precise control over the process. Furthermore, practical knowledge of the process of achieving multistability had been developed for only one type of material, and any idea that involved the use of a new material would require the development of a new material-specific process. It also became evident to the design team, that the forming tools available were not well suited to work on the scale required for the development of the new hinge.

The project team met to discuss these issues (number 6 on the map). Through the discussion it became evident that any development of applications for the multistable process would require a better practical and theoretical understanding of the phenomena by which multistable proprieties were conferred to specific materials. This evidenced the need for further development of the technology's theoretical base by the scientist. It also became apparent that the project needed the intervention of engineers with the expertise to perfect the process and make it more precise, and to develop more adequate tools for the experimental production of multistable material.

In addition, the project team also concluded that their initial rationale of using multistable material to produce wearable accessories for people with limited purchase power may not have been appropriate. Realising how time-consuming and numerous were the steps needed to confer multistable properties to materials, they guessed that producing wearable accessories from multistable material would probably be more expensive than doing so from other materials and processes; for example, using injected moulded plastic. Furthermore, developing wearable accessories using bistable material would not necessarily be the right strategy to interest the accessories manufacturer. A working model of a bistable hinge should be enough to show the potential of the process.

At the end of this meeting, the project team realized that perhaps it was too early in the development of the technology to look for its commercial application, and that a design intervention was not really needed at this stage. At this point it was agreed that the collaboration should be postponed until further development of the scientific research.

After this meeting the design team felt frustrated with the project outcome and spent time thinking on other ways to contribute to the scientist's research. Eventually they had a new idea. Taking on one of the forming processes explored by the scientist, they presented him with a research proposal whereby the design team would design and manufacture test pieces that could help to understand and control this forming process better (number 7 on the map). In return, to make this work, the scientist would have to provide a series of physical parameters. After the design team presented this idea, the scientist acknowledged the merit of this proposal but explained that he was already working on a different project and did not have the necessary resources to pursue this idea (number 8 on the map). In a later interview the scientist reflected: "*your impact has been positive but it led to a negative conclusion for the project, not a bad conclusion, you know, but there is much to do, it needs more time, it needs more*

> *people, it needs a sustained application, and there were not the resources...*" (post-interview, min. 31:08)

> At this point, with no resources to continue the necessary scientific development of this project, the collaboration ended.

7.6.3 Collaboration Output/Outcome

Even though no tangible output emerged from this collaboration, it produced two intangible outputs. On the one hand, it generated a better understanding of the level of development which multistable technology requires before looking for commercialisation. On the other hand, the collaboration helped to identify the expertise needed to continue developing the technology towards commercialisation.

7.7 Case Study 4: A communication tool for Stem Cell researchers

A group of scientists were conducting research on the generation of pancreatic and hepatic cells from human stem cells. Their research is not hypothesis-driven research. Instead, it tries to replicate in vitro the differentiation processes that occur to stem cells in vivo, in the human body. Even if the research can be applied in the future in regenerative medicine for the diagnosis and treatment of illnesses, in its current form it is more focused on the understanding of cell differentiation processes and on how stem cells respond to their environment. The research is still in a very early stage and the research group has been only working together for a year.

Even though the scientific team[17] was not actively looking for design support, it was contacted by the UTTO and invited to meet the design team for a potential collaboration. The scientific team did not have any precedent for working with designers, but they were curious and open to explore the possible forms of collaboration. On their part, the UTTO had an idea in mind and this was part of their reasons to link these scientists to the design team. The UTTO's thought that the designers could potentially contribute to the endeavour of converting the IPR the research group has on its protocols and processes into commercial kits to be sold to other researchers and laboratories. However the UTTO acknowledged in the first meeting that they did not want to force this endeavour upon the collaboration team, and made it explicit to scientists and designers that their support was not conditional on pursuit of their idea.

On the other hand, the design team was looking for a case study in which the scientist was not actively seeking design input, so the collaboration with the stem cell group was ideal. They believed that a case study like this might be an opportunity to intervene directly in the resolution of a scientific research question.

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[17] The scientific team was composed of two scientists: the director of the stem cell research project and a stem cell senior researcher. In this section the first is identified as the research director and the second as the senior researcher.

On this basis the scientists, an UTTO officer and the design group agreed to attend a first exploratory meeting.

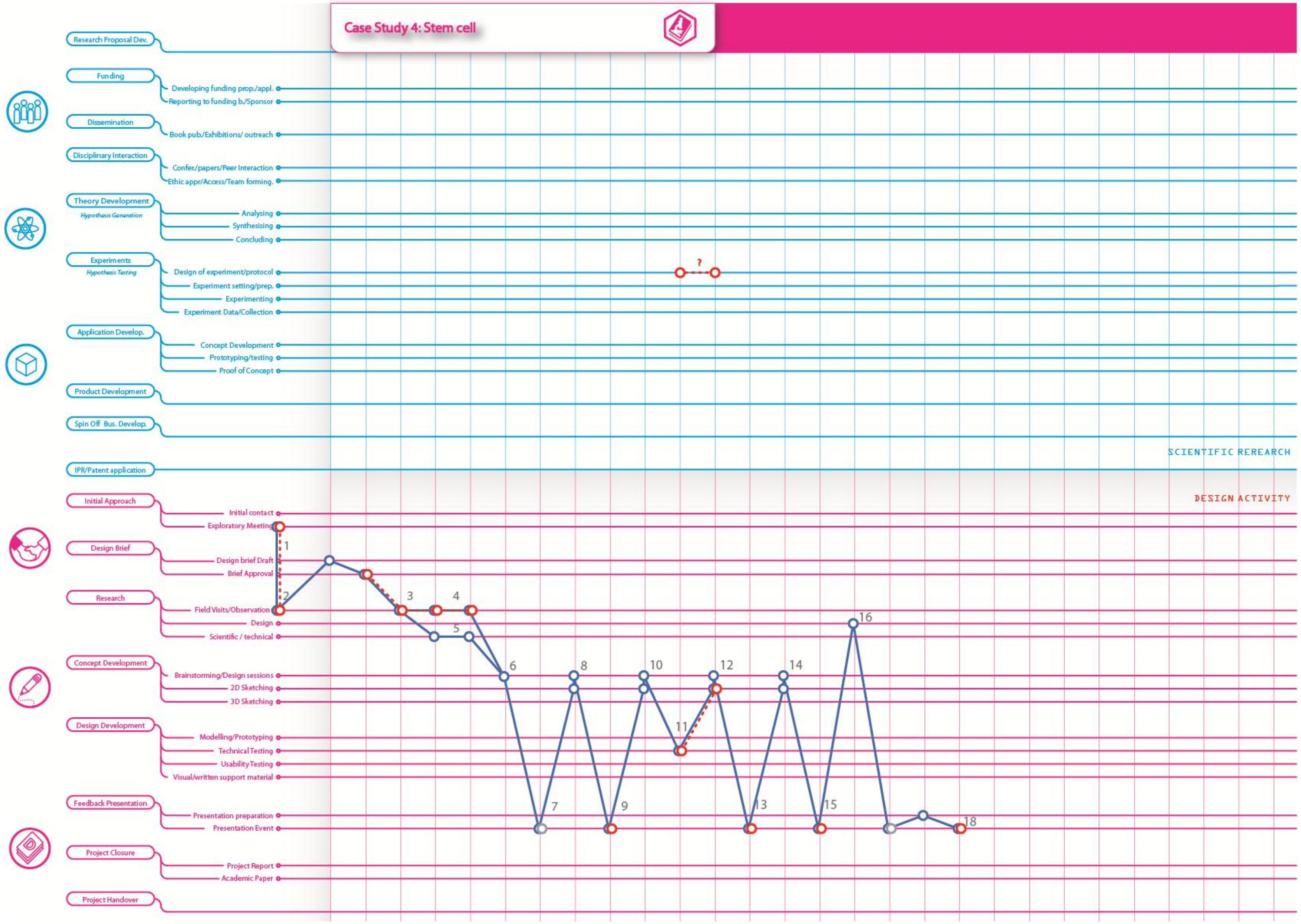


Diagram 7.10 *Mapping of Stem Cell project on the collaboration matrix*

7.7.1 The Collaboration Process

The design team met the research director for the first time at their laboratory (number 1 on the map). First, the designers explained the Design in Science project and some of the case studies they had carried out. They explained that those case studies were facilitated by the UTTO and that they all had in common the fact that the scientists involved had a fixed interest in the collaboration from the onset. The designers also let the scientist know that they were intentionally looking for scientific teams that were not seeking design support and that were at an early stage in their research with no interest in its application in the near future. Also, they intimated that they felt excited about being involved in the stem cell research for its novelty and complexity, and because it was on the cutting edge of scientific research. On his own part, the research director stated that he had never worked in his research with a designer before. He said "*for me design is very far from what we do every day*" (initial meeting, min. 37:35) but he was keen to spent time exploring what designers could do for his research and to see what could come out of a collaboration with designers.

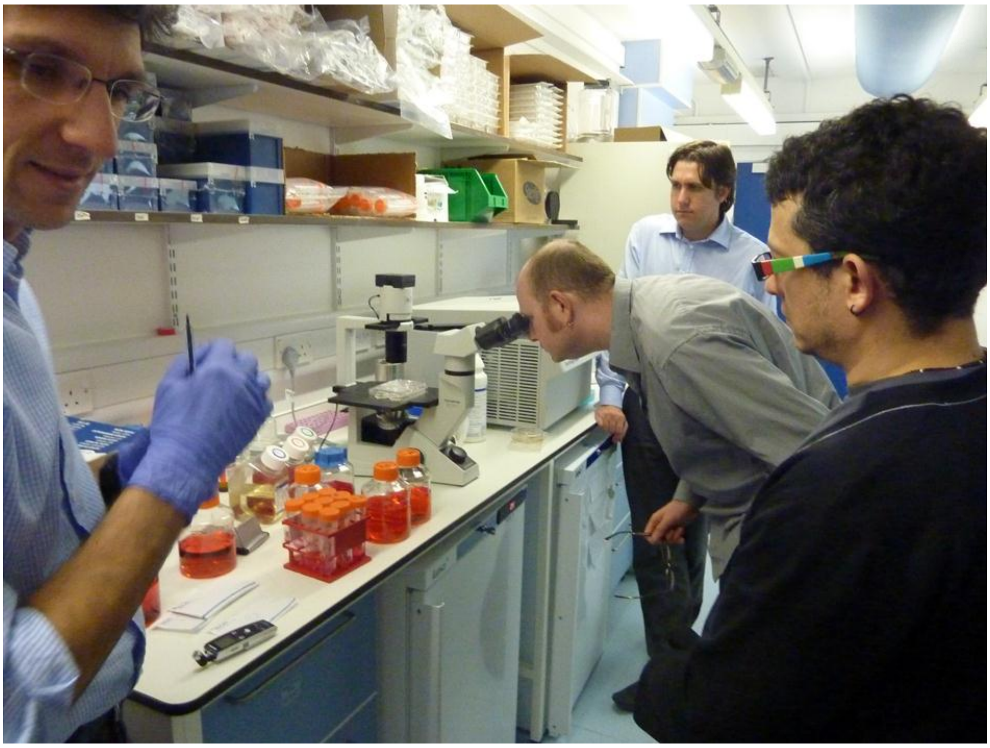
During the meeting the scientist explained what their research was about and also illustrated some of its difficulties and challenges. He said that the main objective of their research was to generate pancreatic and hepatic cells from human stem cells, and that one of its main challenges was to do this in vitro, identifying and controlling the process with the goal of eventually reproducing it in vivo. After the designers had asked some questions about the practical future application of the research they were conducting, the scientist responded that in addition to their potential use for the regeneration of tissue in patients with kidney or pancreas problems, kidney cells could be used for drug testing.

The scientist also spent some time explaining the day to day work in the laboratory, emphasising how time-consuming the processes of cultivating cells was, as well as the analysis of it.

On the other hand, the UTTO officer explained that the UTTO had facilitated the meeting between designers and scientists in the hope that something valuable would result from it. He explained that the UTTO's own IPR resulted from the work that the scientists had done, and that a possible area of work for the designers would be on how to turn IPR into "*a more attractive and commercial proposition*" (meeting, min. 39:40). He suggested that perhaps the designers could develop an "IPR kit" to embody their methods, framing IPR as a product to sell to other labs and researchers. However the UTTO officer also clarified that this was not an imposition and that they would be happy with a different outcome.

The design team then proceeded to tour the laboratory to look at different rooms, work stations and equipment (number 2 on the map).

They also looked at different samples of stem and differentiated cells through the microscope and observed researchers undertaking different experimental procedures and routines.



Picture 7.25 *Scientists guide designers and a UTTO officer on a laboratory tour*

The team also thought that there should be a period for the designers to become familiar with the research, before actually knowing what the design intervention would be. To facilitate this, the scientists invited the designers to attend their weekly laboratory meeting, so they could become familiar with day-to-day laboratory issues and understand the interaction dynamics amongst research staff. It was also proposed that the designers should spend some time shadowing scientists in the laboratory to understand their working practices and routines, experiments and protocols, as well as identifying any potential opportunity for design engagement. To conclude the meeting, the designers agreed to write a proposal for design support.

A couple of weeks after the brief's approval by the research director, the designers participated as observers in a weekly laboratory meeting (number 3 on the map). It was also attended by researchers, PhD students and laboratory technicians, and was chaired by the laboratory director. At the beginning of the meeting, a number of issues were discussed that had the potential to become a design opportunity. These issues related to labelling systems, laboratory materials storage and management. Once actions were agreed to address these issues, the meeting focused on the research work. A PhD researcher made a presentation about her work and results during the last 6 months. While listening, the researchers raised concern about both the validity of her results and the rigor of the study. In particular, they commented on the way in which protocols were followed through, highlighting that they were not followed according to their laboratory standards. It became apparent that during the six months of her research, the researcher did not have the opportunity to become familiar with these particular standard protocols since they were not available as accessible written documents; neither had she discussed them with researchers with more expertise in that area since she was not informed as to who would be able to help her in specific parts of her research. After the meeting the design team discussed this and concluded that if a system for laboratory communication had been in place, this PhD researcher would have been able to produce better results and her valuable time and laboratory resources would not have been wasted. It became apparent that there was no formalised communication system in place to enable new researchers to learn about standard laboratory protocol, and to give them a chance to discuss their research projects with the right people at the right time. There was not a formal mechanism to make evident and accessible those protocols that majorly seem to be tacit knowledge.

Following this meeting, the design team spent 2 days shadowing the scientists in their daily laboratory routine. These scientists had previously arranged things so the designers were able to observe two of the most common experiments carried out in the lab: a laboratory technician conducting RNA extraction[18] and a senior researcher performing cell passaging[19] (number 4 on the map).

During these observation days, the designers paid special attention to aspects of usability in objects and spaces, and considered the methods and procedures employed by the scientists. For example, they noticed issues such as:

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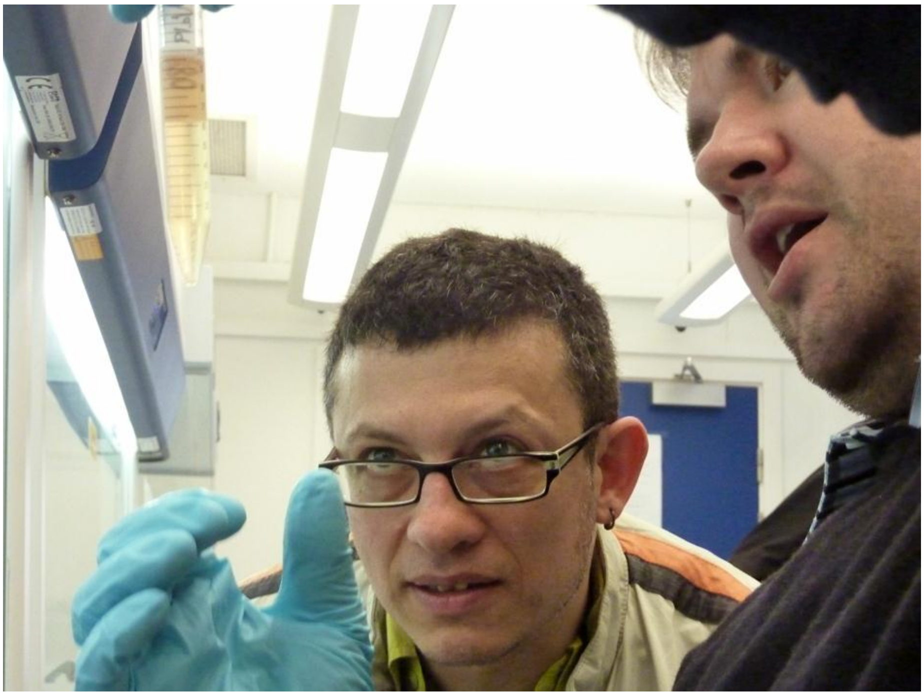
[18] RNA extraction is a laboratory process by which RNA molecules are isolated from biological samples.

[19] Cell passaging is a laboratory process by which cultured cells are separated and transferred into a new vessel.

- Repetitive actions over long period of times (e.g. passing substances from one container to other) causing unnecessary tiredness and the possibility of mistakes being made while distracted
- A series of tagging actions leading to discomfort and errors Informal systems of sharing information about laboratory protocols and equipment usage, such as sticky notes, or handwritten pieces of papers attached to walls and equipment
- Problems with the optimum use of space, such as unused machinery and equipment with insufficient space for operation.



Picture 7.26 *Designer observing an experimental procedure while shadowing scientists*

During and after the observation, as the design team made efforts to uncover design issues and opportunities, they also tried to correlate and understand the scientific notions attached to activities in the lab. By asking questions of the scientists, they developed a better understanding of the complexity of the science they were dealing with, but also realised that to have a sound understanding of these experiments they would need to make explicit the tacit knowledge that lay behind every action of the scientists. Additionally, the designers spent time reading papers on stem cells (given to them by the scientists) and used Wikipedia to clarify ideas (number 5 on the map). Even though the language in the papers (and often in Wikipedia) was technical and therefore difficult for the designers to understand, it helped them to build a good enough understanding of the subject and gradually have more informed conversations with the scientists.

After the observations, the design team met to reflect and to discuss on the project direction they felt was most appropriate to take. They discussed the design issues they detected in relation to usability of objects and spaces, and the methods and procedures employed by the scientists. Although they found them interesting as a design opportunity, they were too close to the design challenges which a product designer acting as a consultant would normally have. Consequently, they decided to look at another of their findings, the communication problem amongst scientists detected at the weekly laboratory meeting, since it was a less conventional product design challenge and, if adequately resolved, would have considerable impact on the scientists' research. After some discussions they agreed to choose this as the design area in which they wanted to work.

7.7.2 The Design Process

To begin the project, the design team decided to do an initial mapping exercise. They chose to map a standard laboratory experiment so they could first confirm and correct their understanding of the relevant science, next gain an initial insight into communication issues amongst scientists while interacting and then outline a first draft of a "laboratory communication tool" to enhance scientific interplay/ communication/ interaction in scientific research.

They brainstormed a suitable mapping structure and concluded that their map should consist of three levels (number 6 on the map).

Level 1: The overarching level, it should show the experiment *process* (Protocol)

Level 2: An intermediate level, including its *method* and details of the process input (Variables: materials, times, etc.)

Level 3: The "deep end" level, including the experiment rationale (information about decision making, people involved and associated narratives such as direction and focus at any particular stage).

Even though the designers favoured the "laboratory communication tool" direction they still were not sure how that idea would be received by the scientists. The designers were afraid that this kind of problem would not be what the scientists were expecting, but most importantly that the scientists would perhaps take this as a criticism of the way they were running their lab, and hence the collaboration would be at risk. For this reason, the team decided to discuss their ideas with the UTTO officer before talking to the scientists, to benefit from his advice and expertise.

During the meeting with the UTTO officer, (number 7 on the map) the designers explained the three main areas in which they thought it would be possible to make a useful contribution to the scientists' research:

1. Communication improvement: the creation of tools for effective communication and sharing of information between scientists. These tools would make tacit knowledge explicit and make it easier for new and less experienced researchers to know and adopt laboratory standard practices.

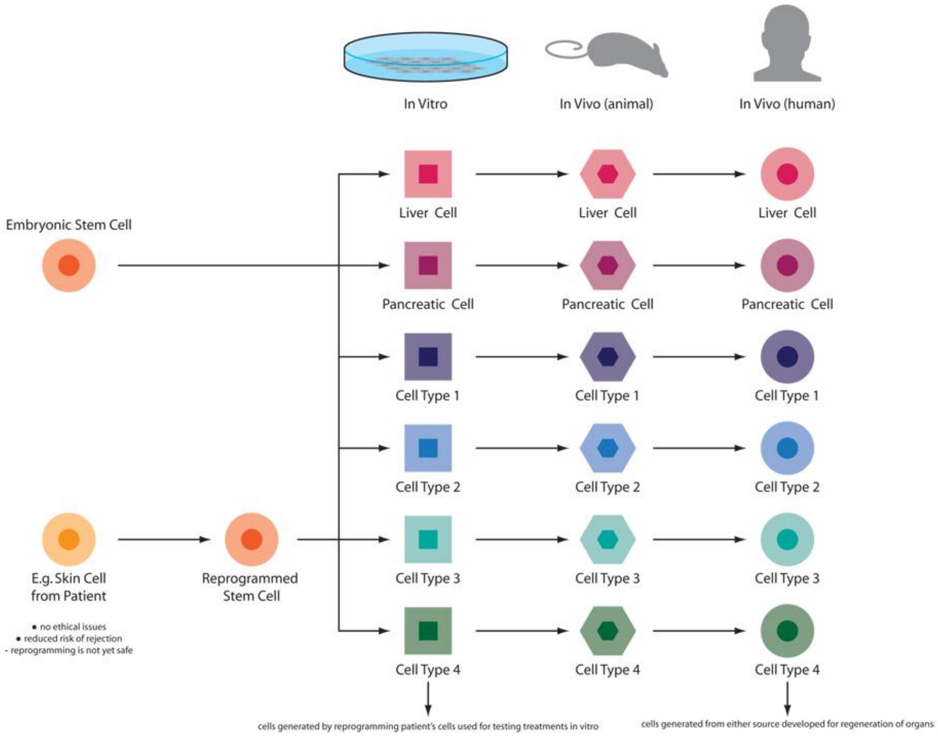
2. IPR kit: the design of commercial packs containing processes and protocols with IPR developed in the scientists' lab, to be sold to other laboratories and researchers. The packs would contain "ready

to mix" biological and chemical materials and associate protocols and instructions.

3. Non-medical application concepts: the generation of speculative future applications of stem cell technology, with the purpose of finding further themes for collaboration.

The UTTO officer commented on the suitability of these ideas. He found the communication tool idea interesting but thought the task of unifying protocols difficult, since in his view each scientist would have his/her own variation of those protocols. Regarding IPR, the UTTO officer stated that producing biological and chemical materials for sale went beyond the scope and capabilities of the lab. Also, he informed the designers that there were already commercial laboratories manufacturing this type of product. He also highlighted that working on protocols with an associated IPR would be a task beyond the designers' area of expertise. This contrasted with his initial idea of having designers contribute in this area. On the non-medical application concepts, the UTTO officer expressed concerns about ethical issues as well as the technological difficulties associated with the development of such applications. Other than these criticisms of the ideas, the UTTO officer did not see any problem in presenting the communication tool idea to the scientists, and he was confident that the scientists would be open to comments on the efficiency of their communication methods. Since it was clear to the designers that the communication tool idea was the strongest in terms of feasibility and convenience, they confirmed their intention to develop it.

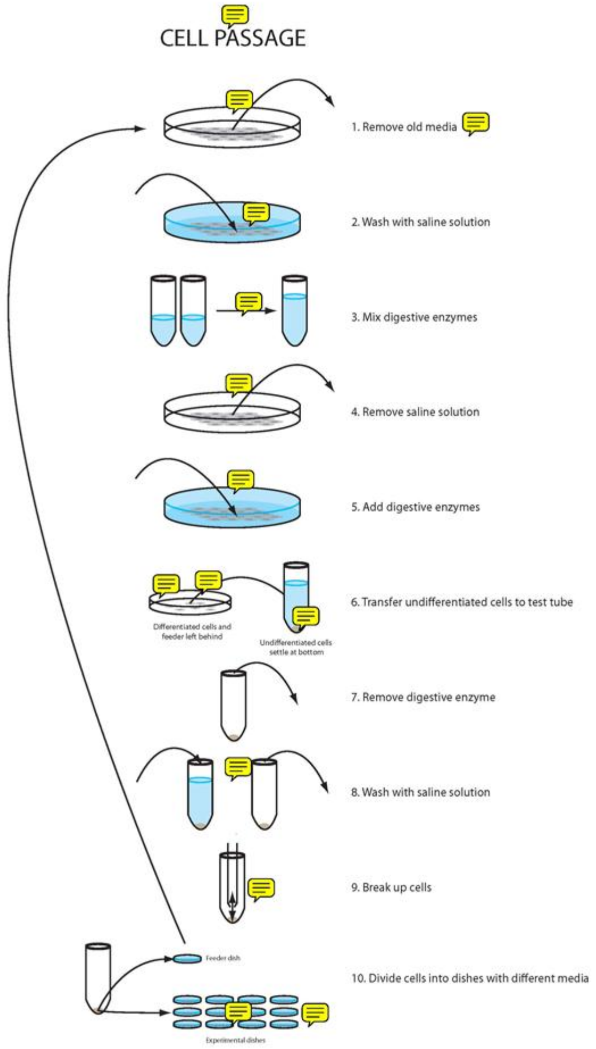
After this, the design team developed a visualisation of one of the procedures they had observed (cell passaging). They also outlined their initial concept of a communication tool following the 3 levels generated in their previous brainstorming (Process, Method and Rationale). This concept took the shape of a PDF document, in which it was possible to navigate from an initial map of the stem cell research (Process) to an associated experimental procedure (Method) towards details specifying the rationale of the experiment and other information such as associated researchers, special notes, etc. (number 8 on the map).



Picture 7.27 *A page of the initial designers' concept for a communication tool*

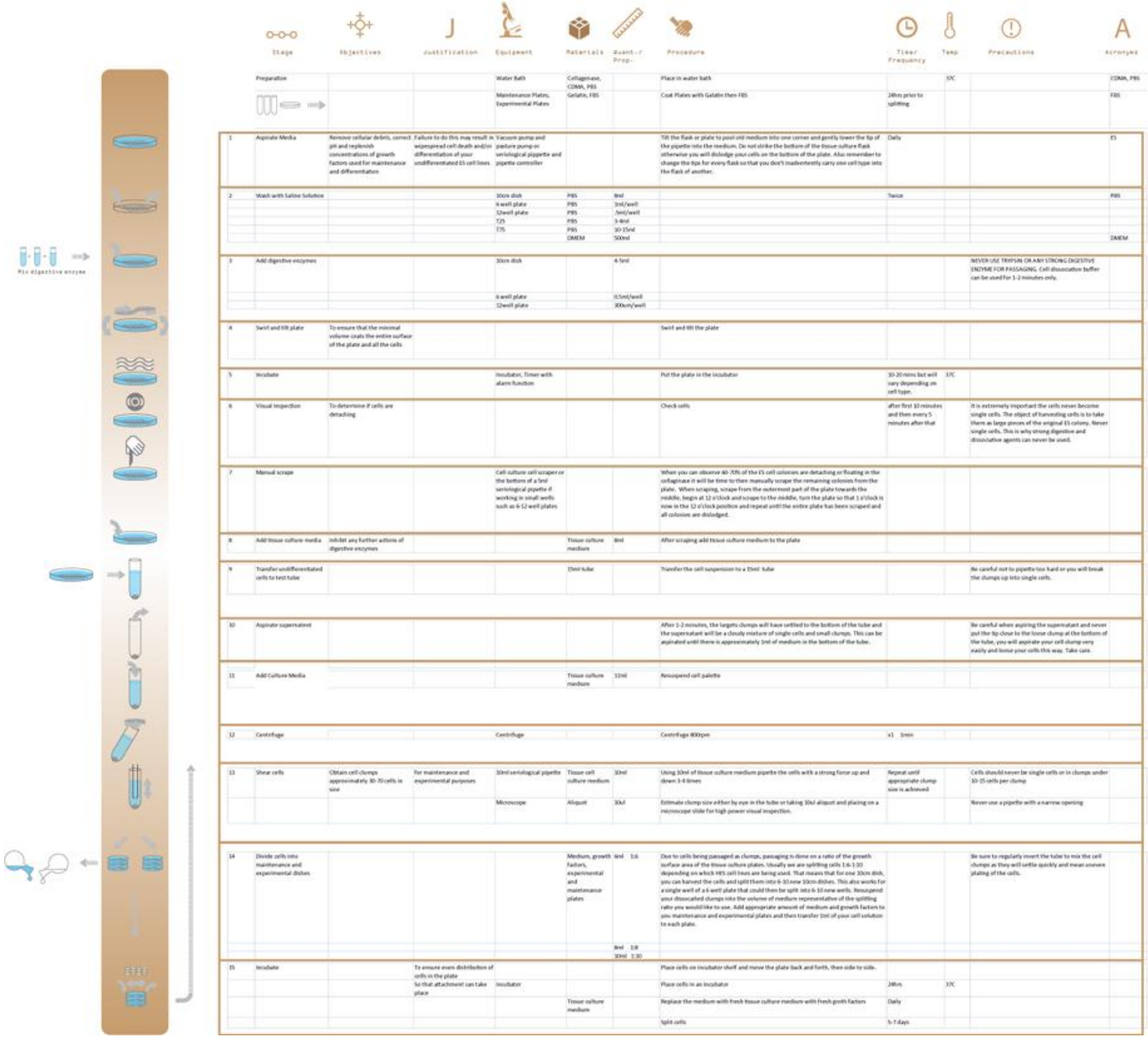
The design team then prepared a presentation of this initial design and met the senior researcher. In the meeting, the design team was interested in the initial impressions of the scientists of their communication tool, but also wanted to clarify questions about stem cell research and to confirm if their understanding of the science was sound (number 9 on the map). This duality of purpose became a characteristic of all subsequent meetings, helping the designers to continue with the project and learning about the science at the same time. The process of developing ideas always brought new questions from the designers, and once they were answered by the scientists, they would integrate this into their ideas and new questions would arise in an iterative cycle.

This meeting concluded with a positive appraisal of the communication tool by the scientists and a discussion of its potential use. The scientists thought that this proposal could be useful for inducting new PhD students, giving them easy access to protocols, and also suggested that it could also be employed to explain and exchange protocols and procedures with other labs. The designers also thought that by developing a map, the foundation for a “system for a fast writing and updating of protocols” could be implemented. This development suggested a new possible form of designer contribution to scientific research: knowledge transfer between scientists. After this meeting the designers agreed to develop the tool further and to send the most recent version of the cell passaging protocol to the senior researcher for his comments (number 10 on the map). He returned the visualization to the designers with detailed annotations on each stage of the protocol. These annotations made explicit the great amount of information that existed in the scientists' minds in the form of tacit knowledge: see Picture 7.28 (number 11 on the map).



Picture 7.28 *Designers' initial visualisation of a protocol with scientists' comments/notes*

The designers then codified the new information, and introduced a range of parameters for cell passaging protocols. Based on that, the designers created a “protocol matrix” that made it possible to specify these parameters in great detail at every stage of a protocol (number 12 on the map).



Picture 7.29 *The protocol matrix developed to communicate experimental protocols in great detail.*

The design team also developed an interactive visual system based on a diagram of the various stages of differentiation[20] of stem cells. This diagram was the base from which to access different associated protocol templates, which would show associate "protocol matrixes" as a protocol library. The designers developed the user architecture[21] of their interactive system through wireframes[22] and the tool was embodied as a web page, so the scientist could access it off- and online, and would be able to record, edit and share experiments with colleagues.

In a further meeting, a mock-up of this was presented to the senior scientist (number 13 on the map). He confirmed again that this tool would be very useful to introduce the laboratory protocols and experiment practices to PhD students and new scientists. However he did find it less useful for experienced scientists as a consulting tool since they would have all these experiments fully memorised. Additionally, he thought that the tool would be useful for these scientists if used as a laboratory book to record and monitor experiments, especially if operated from an electronic mobile device such as an iPad. Eventually, some amendments to the sequence and

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[20] Stem cells grow into develop functional cells (e.g. Liver cells, pancreas cells, neurons, etc) through several stages of "differentiation".

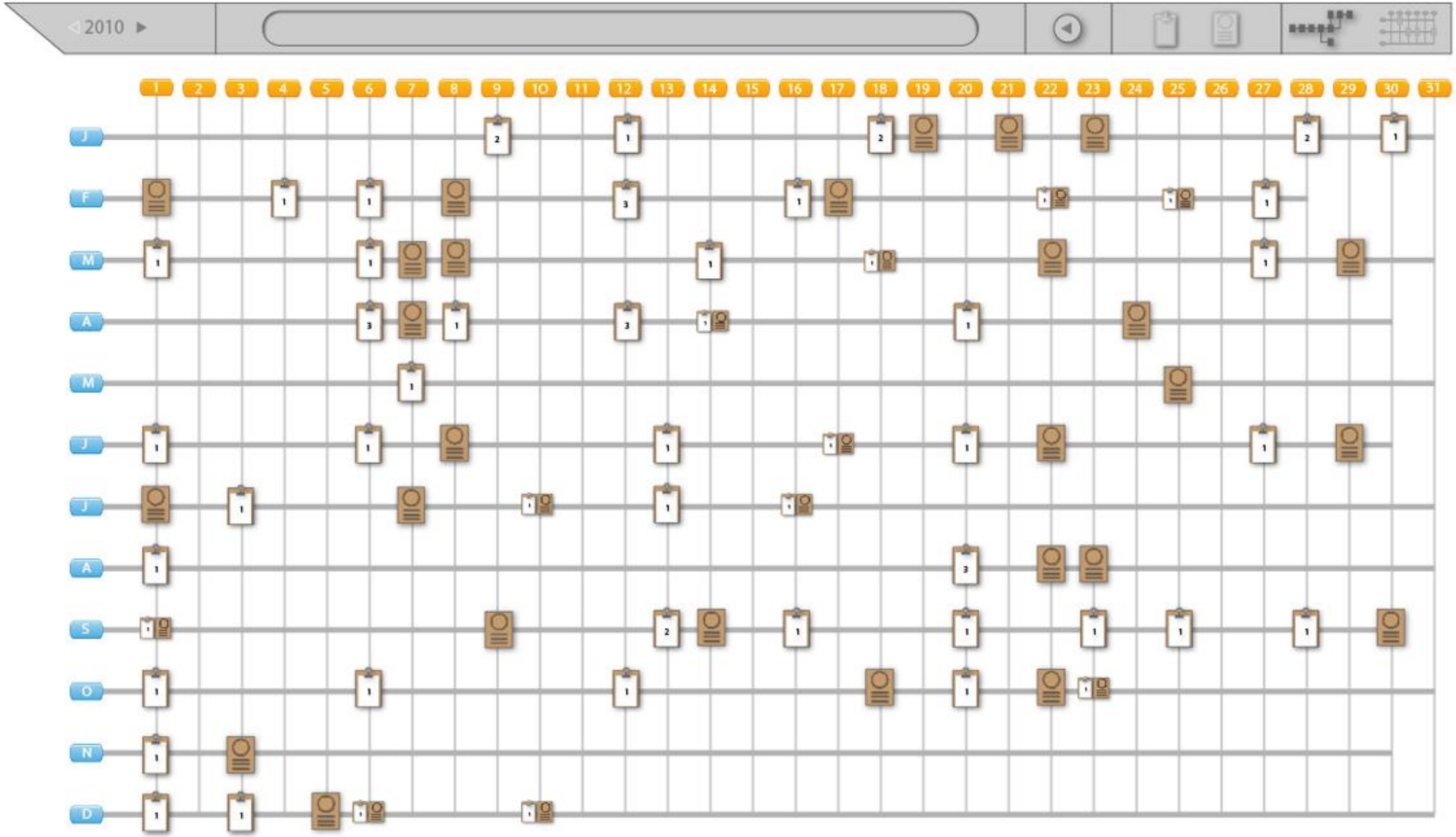
[21] Information architecture is *"the art and science of structuring and organizing the information in products and services, supporting usability and fundability. More basic concepts that are attached with information architecture are described below*." http://en.wikipedia.org/wiki/User_experience_design#Information_Architecture

[22] A wireframe is *"a visual guide that represents the skeletal framework of a website"* http://en.wikipedia.org/wiki/Website_wireframe

stages of differentiation were suggested and carried out, as well as the incorporation of a calendar interface to track the progress of projects over time.

After some final corrections the design team met both the research director and the senior researcher to present the communication tool (numbers 14 and 15 on the map). The designers explained that the tool had been designed to serve as a research map, accessible to all scientists from the centre in order to read and use existing agreed protocols. In this way tacit knowledge could be made explicit, and research could be conducted in a more rigorous way. Also, it was explained that the tool was becoming similar to an electronic laboratory book.

The designers described the structure of the tool, and its main components: a map, a calendar and the protocol matrix. They used an analogy to explain the overall function of the tool. They compared the tool with the drawings that architects, designers and engineering use for their work. The tool, like the maps, is a visual, explicit, condensed and shareable representation of their work. After this and further illustration of the different content and navigation features, the scientists offered their feedback.



Picture 7.30 *The index page of the laboratory communication tool*

They highlighted some aspects of the tool that needed improvement: the navigation should be easier and more direct, the tool should have a validation feature (so experiments can be validated by peers), and it should have an integrated search function, so users could look for protocols and documents quickly. Also, both scientists agreed on the need to enable the system to connect to laboratory reading equipment, so in that way raw data could be downloaded directly into the tool.

The scientists also stated that the tool could be very useful and the research director pointed out its commercial potential. He also mentioned the importance of undertaking a marketing study to confirm the commercial potential the tool may have for other labs in both the education and the commercial sectors. He suggested contacting the UTTO for this.

The meeting concluded on an agreement for the designers to make amendments to their current proposal and to present the results to the wide research group. There was also agreement on a project development sequence in 3 stages: first, a refinement of the protocol matrix, secondly the development of the tool as an electronic laboratory book, and lastly an additional development of it as an administrative tool. Finally, the scientists expressed their interest in supporting the prototyping of a pilot tool and undertaking an initial trial of it in their lab.

As the tool evolved with new functions to become an electronic laboratory book, the designers decided to search for existing Electronic Laboratory Notebooks, or ELNs (point 16 on the map). They found different models already on the market, and most of them had already integrated the functions the designers were considering in their proposal. Also, they seemed to be quite generic and not targeted to the needs of specific sciences. At this point, it became apparent that the strength of the designers' concept was that their proposal was tailored exclusively for research on stem cell, and in addition, it was developed using a navigation system based on a graphic language that made its interface intuitive and easy to use.

Since the design team had little experience in developing interactive design, they decided to discuss their idea with someone better qualified in this field. They contacted someone with experience of implementing ELNs in industrial and academic labs (point 17 on the map).

After the designers presented their concept to the ELN expert, he confirmed the potential of the interface developed by the designers because of its visual character, but he was emphatic in highlighting the programming and development complexity of an ELN, encouraging the designers to contact existing ELN producers to see if they could incorporate their ideas and visual interface on existing ELNs, rather than trying to develop the concept on their own. He also mentioned to the designers that their skills could be used to fine-tune existing ELN features so they could address day to day ‘micro work flows’ on labs.

At the end of the meeting, the ELN expert showed the designers a working sample of an ELN. Its interface was based on the Windows file management and, with the exception of its calendar feature, it already had all the current and recommended features of the designer’s laboratory book proposal such as a search menu and the experiment validation function, amongst others.

After the meeting with the ELN expert, the design team re-evaluated their approach, recognising that perhaps it would be more sensible to ask the scientists to try existing ELNs before embarking on a time consuming and expensive development of a new one. Only then, if existing ELNs did not match the scientists’ needs, would the designers intervene again, either to modify existing commercial ELNs to fit the stem cell scientists’ needs, or to develop a new one based on the designers’ concept already initiated. The design team also thought that the protocol matrix they developed had value on its own and could still be developed for use in the laboratory as a communication tool between scientists, especially between experienced and novice researchers.

With this in mind, the design team prepared a presentation with a summary of the whole project and an explanation of their position regarding its continuation. After presentations to both the research director and the senior researcher, they agreed on the need of trying an existing ELN before continuing to develop the designers' communication tool concept. This became even more evident after a discussion about the potential relation cost-benefit of developing the communication tool. If the tool was not developed as a commercial product and sold to other labs and scientists, the scientists' lab would probably be unable to afford to develop it.

Also, the designers discussed that if this project were to continue, they would have to rethink their concept from the beginning, since they did not look at it as a laboratory book from the project onset. They thought that the DLE should depart from current information management practices associated with analogue laboratory books. They also thought that further on-site observations focused on laboratory book related real life practices, should take place.

Pondering the possible complexity and cost of the project, and considering that the "Design in Science" project was nearing an end, the designers and scientists decided to end the collaboration (point 18 on the map).

7.7.3 Collaboration Output/Outcome

The main outputs from the stem cell collaboration were i) a matrix for recording protocols and ii) a concept for a laboratory communication tool/DLE. The collaboration also served to make tacit knowledge on Cell Passaging protocol explicit and integrated through the protocol matrix. Additionally, the collaboration offered the scientists the opportunity to reflect on their internal communication practices and to think about the need to improve them.

7.8 Case Study 5: Communicating Biophotovoltaics

A multidisciplinary team of scientists from several university departments (including Biochemistry, Plant Sciences and Chemistry) were collaborating on a research project to develop Biophotovoltaic (BPV) technology. This technology is based on the possibility of obtaining electric energy from the photosynthetic processes of living organisms, and the main purpose of their research is to understand the chemical and biological mechanisms that govern this phenomena. To this end, the scientists developed an initial proof of concept prototype that utilised the photosynthetic processes of algae and generated a few nano-watts of power when a light source was directed towards it. The device was developed to enable the scientists to obtain data to support their theoretical development and publish their findings. After the success of this first device the scientists filed a patent and focused on building a more sophisticated device with the intention of increasing its electrical potency.

Even though the scientists believe that there is commercial potential in photovoltaic technology, their research is in its very early stages, and they consider that it will take 20 years before commercial applications such as photovoltaic cells are available on the market.

As part of their research dissemination activities, the scientists were committed to participate in a science exhibition in London. They were planning to set up a stand with explanatory posters about the Biophotovoltaics technology and to exhibit one of their devices, possibly powering an electronic clock or a small fan. By participating in this exhibition, the scientists were aiming to explain the technology to the general public and to illustrate its potential.

The design team heard about the research on biophotovoltaics from a department enterprise champion they had interviewed at the beginning of the *Design in Science* project, who knew about her colleagues' intentions to participate in the London exhibition and thought it appropriate to put them in touch with the design team. She thought that the designers could contribute to make the exhibition and the device "*look appealing and user friendly*".

Since the designers were actively looking for a case study in which the research was in its early stages, they arranged to meet the photovoltaic research team.

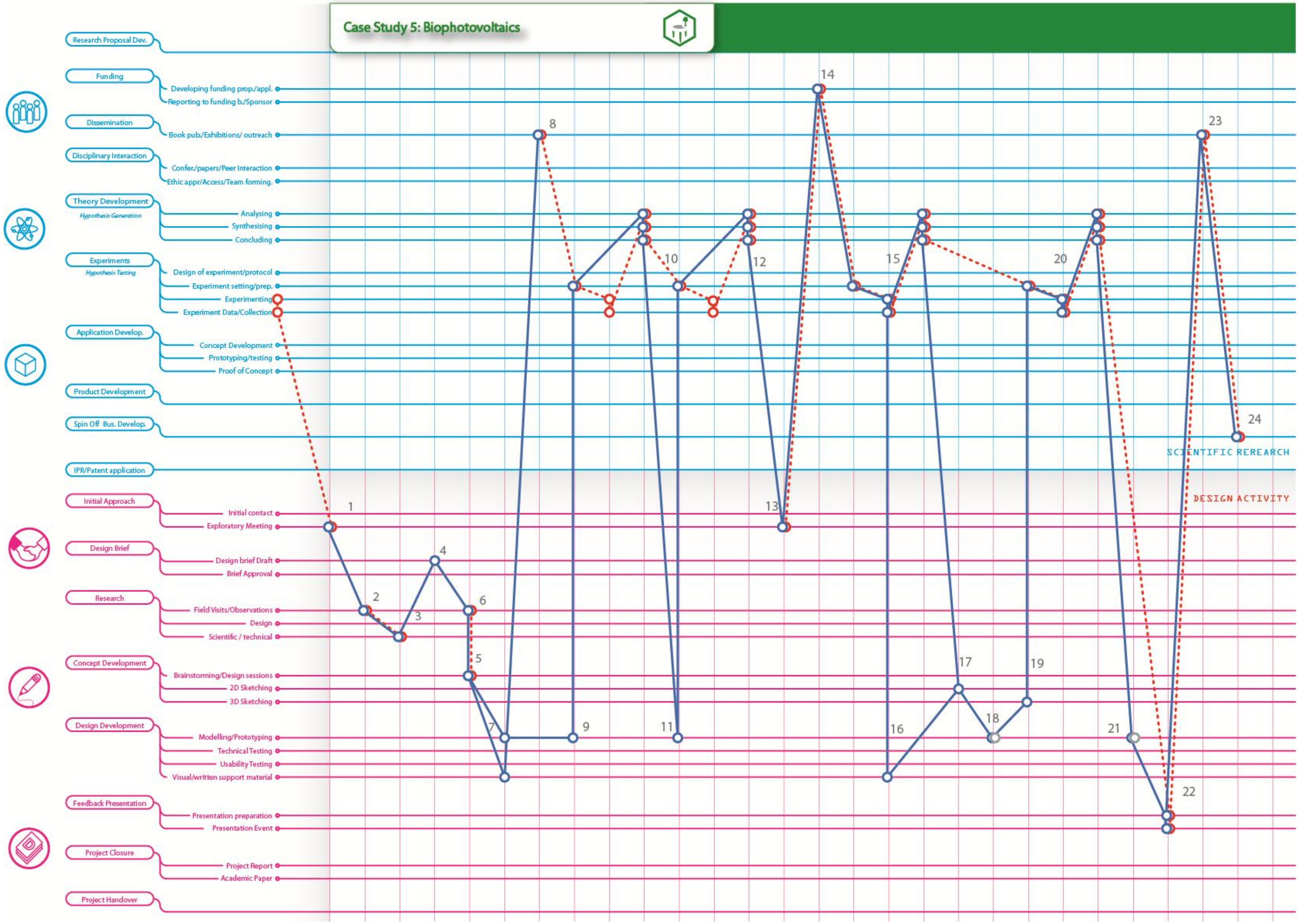


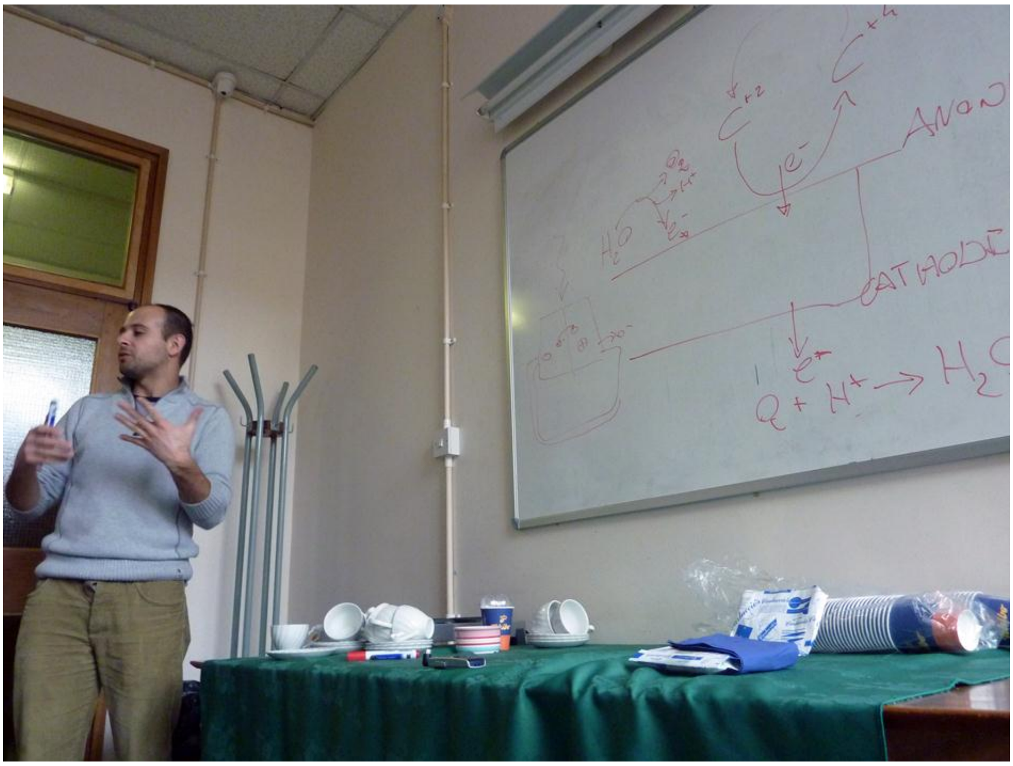
Diagram 7.11 *Mapping of Biophotovoltaics project on the collaboration matrix*

7.8.1 The Collaboration Process

The initial meeting was attended by several scientists (PhD researchers, researchers and senior researchers) from different departments involved in BPV research and the design team (Point 1 on the map). Although the department enterprise champion (who was also part of the research team) had explained to the scientists that the designers could potentially contribute to the exhibition, they were not sure how this could happen. One of the scientist said in a later interview that "*Initially we didn't know what we could actually do together*" (post-interview min. 0:20), and that it took some time before they really understood what the designers were able to do.

During the initial meeting between the designers and the photovoltaic researchers, the designers explained the *Design in Science* project and illustrated some of the projects they had already conducted in an attempt to encourage the scientists to think about possible areas for design intervention in their research. The researchers on their part explained the interdisciplinary character of their research, having involved several scientists from different departments looking at specific discipline-laden aspects of the photovoltaic technology.

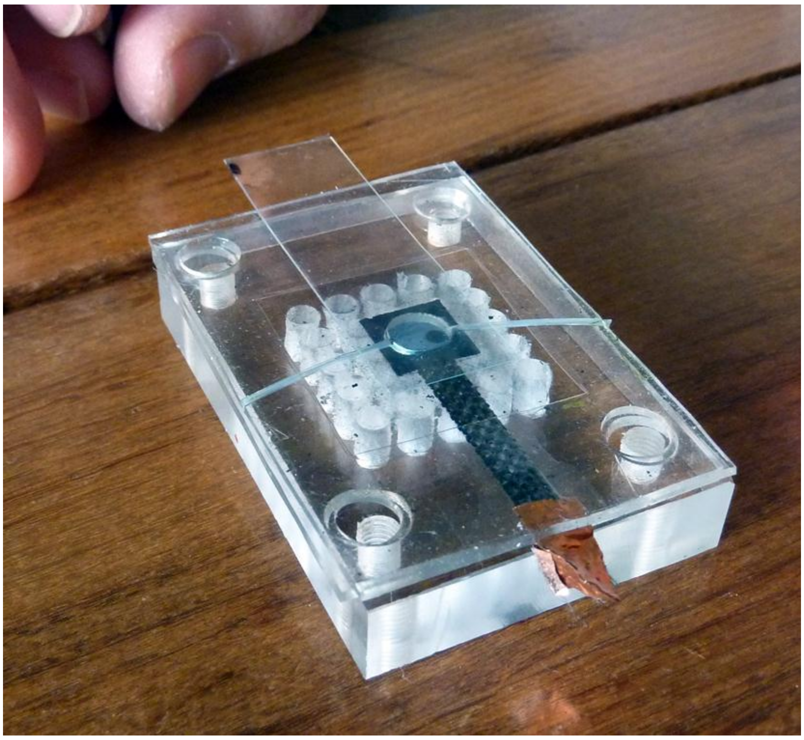
During that meeting the scientist in charge of developing the photovoltaic devices explained the technology and its main scientific principles. After this, designers and scientists discussed possible collaboration opportunities and concluded that the science exhibition in London might be a good starting point. They agreed that the designers would help the scientist to produce a poster for the exhibition and a demonstrator, to communicate the photovoltaic technology principles to a non-scientific audience. The designers also suggested that the poster could be populated with visualisations of future applications of the technology, to make the technology easier to understand.



Picture 7.31 *Scientist explaining biophotovoltaic technology in an initial meeting with the designers*

In a subsequent meeting the designers met the scientist that had developed and manufactured the proof of concept BPV prototype (point

2 on the map). He explained the scientific principles governing the BPV device and his plans to develop it further in order to improve its electrical efficiency. During this meeting, the designers asked a few basic questions that made the scientist wonder if they would be able to understand the technology well and fast enough to be able to make a meaningful contribution. At the end of the project, in an informal conversation talking about the development of the collaboration, the scientist revealed that his rule of thumb for knowing when someone really understood a subject was that the answers to their questions could not be found on Wikipedia; he call this the “Wikipedia threshold”. He also confessed that he was positively surprised at how quickly the designers passed that threshold, after a couple of meetings.

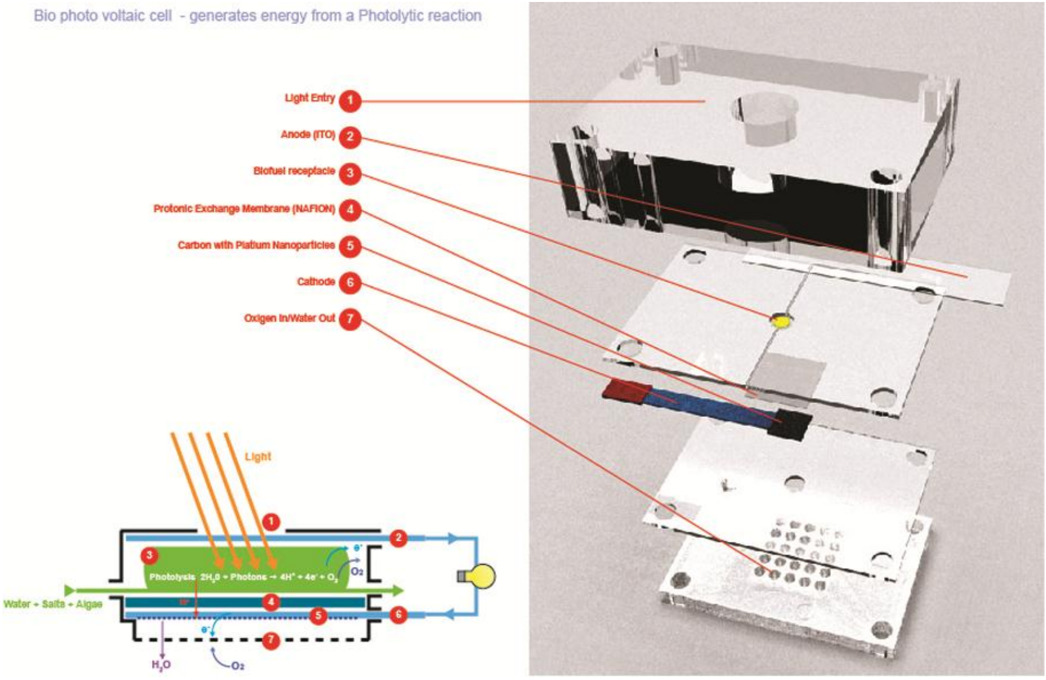


Picture 7.32 *The scientist biophotovoltaic proof of concept prototype*

The designers were conscious of their knowledge gap and felt they needed to understand better the scientific principles underpinning biophotovoltaic technology, so they asked the scientist to point them towards suitable literature on the subject. Later he sent a couple of seminal scientific papers he and other colleagues had written, and some Wikipedia links (point 3 on the map). From this point, and during the whole project, the designers constantly had to study relevant chemical, biological and electrical principles.

7.8.2 The Design Process

Following this meeting, the designers prepared a project brief summarising the scope of the collaboration and outlining their expected contribution as agreed in the previous meetings (point 4 on the map). At the same time, they decided to create some initial visualisations of the scientist's device, using graphic diagrams and 3D computer models of it. These visualisations had a double purpose: on the one hand to verify with the scientist if their understanding of the technology was accurate, and on the other to begin generating visual material for the exhibition poster. With just a few minor observations made, the scientist was so impressed with these initial visualisations that he acquired 3D modelling software so as to be able to make similar computer-generated illustrations in the future.



Picture 7.33 The scientist's biophotovoltaic proof of concept prototype

As one of the design tasks was to develop visualisations of future applications, the design team decided to run a brainstorming session. They invited scientists from the Biophotovoltaics research team and some other designers and members of the UTTO. Their idea was to generate as many future application concepts as possible, having the scientists there to contribute ideas and also to help confirm the scientific validity of the ideas.

The participants developed ideas in mixed teams of designers and scientists and presented them to each other using sketches and diagrams (point 5 on the map). The concepts developed ranged from small domestic objects to electricity-generating mega-structures. After the brainstorm, 6 main concepts were selected and further developed by the designers. They also created 3D computer models of them to render realistic images of the concepts, and to use them in the design of a poster for the London science exhibition (point 6 on the map): see Picture 7.34

BIOPHOTOVOLTAICS

CONCEPTUAL DESIGNS FOR A NEW SUSTAINABLE TECHNOLOGY

Biophotovoltaic devices are biological solar cells that generate energy from the photosynthetic activity of living microorganisms such as algae. Biophotovoltaics is a new technology with current prototypes only recently being developed in the laboratory. Current research involves international collaborative efforts between biologists and engineers, with biologists working to understand the nature and behaviour of algal cells, and engineers optimising the functionality of the devices.

A scientific team at the University of Cambridge has worked with a group of designers to create a series of conceptual designs to demonstrate potential future applications of this technology. The commercial application of algal biophotovoltaic devices may be 20 years away but these ideas clearly illustrate their unique properties as a potential renewable energy source.

Biophotovoltaic devices are environmentally friendly and easy to manufacture compared to conventional fuel cells and solar panels. Algae, the bio-electrical catalyst, require only water and sunlight to generate energy. No harmful chemical waste is produced during this process, and once exhausted the devices are easy to recycle. In addition to generating power, these devices can be used for water desalination.

SCIENTIFIC PARTNERS
The Algal Bioenergy Consortium
Department of Chemical Engineering and Biotechnology, CREST Lab
Department of Biochemistry, Howe's Lab
Department of Plant Science, Smith's Lab
EPSRC

BIOPHOTOVOLTAIC SOLAR PANEL
A modular system of bio-solar panels containing algae which can be mounted on a building
LOCATION: Inland, near a water supply, warm climate
CAPICITY: Similar to existing solar panels – meets energy requirements of the building they're mounted on

BIOPHOTOVOLTAIC FLOATING GENERATOR
A small group of algal solar collectors mounted on floating buoys which also harvest desalinated water
LOCATION: Near-shore, warm climate
CAPACITY: Several units provide electricity and desalinated water for a small coastal community

BIOPHOTOVOLTAIC FLOATING POWER STATION
A field of large floating algal solar collectors
LOCATION: Offshore, warm climate
CAPACITY: Provides electricity for a large coastal settlement

BIOPHOTOVOLTAIC MASTS
A forest of algal solar collecting masts which draw water either from the ground or from rainfall
LOCATION: Inland, warm climate, close to water table or in area of high rainfall
CAPACITY: Can be scaled to provide energy needs of a local community

ALGAE TABLE
A table incorporating a bio-solar panel which stores energy to power a light in the evening
LOCATION: domestic use, warm climates
CAPACITY: The lamp

Picture 7.34 *Poster with visualisations of future application of biophotovoltaic technology*

Simultaneously, the designers visited the scientist’s laboratory for a demonstration of the latest devices on which he was working (point 6 on the map). After this visit, the team decided to develop the “algae solar panel”, one of the concepts from the brainstorm. The team was hoping to have it ready and functioning for the science exhibition in London. The purpose of this was to show the public how future photovoltaic devices could be embodied and to give the visualisation of the future applications more impact and credibility amongst observers.

As the date of the science exhibition in London was looming large, the designers finished producing the poster, but difficulties in obtaining key materials prevented them from having the algae solar panel on time. The poster was printed and exhibited together with one of the devices prepared by the scientists; it attracted attention from the public and became a vital piece to explain the technology (points 7 and 8 on the map).

After the London exhibition, the team continued building the algae solar panel. When eventually finished and tested by the scientist (points 9 and 10 on the map) it did not generate as much energy as expected, but it served as the basis for the development and construction of a second improved device. This first device brought an unexpected benefit to the scientist’s research. As the size of the device was considerably bigger than any other BPV device he had built before, and as the water produced from the biophotovoltaic process pooled inside the object's oval shape, it became possible for the scientist to measure it. Thanks to this, he was able for the first time to confirm empirically that water is produced in biophotovoltaic processes and to prove that BPV technology can potentially be used as a means to desalinate sea water. A second iteration of the device was built and even though it was better at producing electricity that the previous one, it served to demonstrate that large devices do not perform as well as small ones on similar configurations (points 11 and 12 on the map).

Picture 7.35 *Algae solar panel designed and manufactured by the designers*

The success of the poster in the science exhibition and the positive results of the algae solar panel become a turning point in the collaboration since it demonstrated the designers' capabilities to the scientists and it helped to build a trusting relationship between them. At this point the design team thought that the project could be taken further by developing and manufacturing one of the concepts initially included in the poster: the biophotovoltaic table.

The biophotovoltaic table was conceived as a future domestic product integrating a table and lamp powered trough biophotovoltaic energy. The designers thought that domestic familiar objects (such as a table and a lamp) would be the ideal media to communicate how BPV works and its potential. For this reason they developed a table as a simple and neutral piece of furniture that would not compete but harmonise with the BPV technology.

The design team presented the idea to the scientist, arguing that the table could be used to introduce the technology to a wider audience, to raise the biophotovoltaic research profile with the public, to explore the application of the technology and to promote collaboration between designers and scientists inside and outside the university (point 13 on the map). Also, they believed that developing the table would bring some interesting scientific research challenges for the scientist, especially regarding the scaling up of BPV devices. Additionally, they also thought that by increasing public awareness about BPV technology in circles outside the scientific world, it could potentially attract investors. As part of their proposal, the designers included a plan to take the table outside the normal dissemination channels of science and exhibit it in national and international design exhibitions, during reputed design events such as the London Design Week and the International Furniture Fair in Milan.

Picture 7.36 *Algae table concept presented to the scientist*

The scientist reacted positively to the proposal and initiated consultation with his colleagues to seek support and funding (point 14 on the map). Also, he suggested that instead of using algae for the photovoltaic components of the table, it would be better to employ moss, which was a more resilient organism and would not need to be directly exposed to sunlight in order to generate electricity.

While waiting to hear from his colleagues about the funding, the scientist started to develop some devices based on the utilisation of moss. He developed and tried different device configurations, seeking to increase the production of electricity and to improve current stability. The designers collaborated with the scientist in this process, suggesting materials and discussing the advantages and disadvantages of the different models he developed (point 15 on the map). Also, the designers helped record the configurations of the different models through schematic visualizations (point 16 on the map). During this process the designers also participated in some of the scientist's experiments in order to evaluate the electrical performance of the models. After a few iterations, the best configuration was identified and the designers started to develop a suitable version for the table, to ensure that it was producible in low quantities. From this moment the device was named the "moss pot" and the table was branded "the moss table".

Picture 7.37 *Several configurations of the "moss pot"*

Parallel to the development of the of the moss pots, the design team also designed the shape and components of the table (point 17 on the map). While at the beginning of the project it was expected that the electricity produced by the BPV devices would be sufficient to power the table's integrated lamp, the project team realised that it would take some time, perhaps years, before this was possible. This made the designers reconsider the idea of having an integrated lamp and to consider alternative designs. In the end they thought that the image of the table and its integrated lamp conveyed the potential of the BPV technology better than the other design alternatives they developed, and because of this they decided to keep it in its original configuration. They thought that rather than presenting it as a working prototype, they would show it as future product concept. Together with the scientist, they decided that when exhibited, the table should be accompanied by a small array of "moss pots" powering a small electronic device to demonstrate that the technology actually works.

Although these design decisions were taken principally by the designers, the scientist participated in the discussion about the table's integrated lamp. At the beginning he was not that keen on integrating the lamp, but he eventually agreed and trusted the designers' judgement. The scientist later revealed in an interview after the project that *"At some point I remember thinking: why do we have a lamp on the table and not something else? And then I said to myself... this is not my business, I mean, they are supposed to care about that"* (post-interview, min. 50:55).

After confirmation of initial funding for the construction of the table, the design team undertook the finalisation of its design. Through hand sketches and computer models, the designers developed its shape and defined its size, proportion and overall constructive details. As the table was intended to be a one-off object, the designers did not have as many formal and material constraints as would normally happen with a product for mass production. They used simple lines, and soft curves for the design of the table to make it attractive and simple. They designed both the lamp and the table following their archetypical form in order to make them recognisable as a table and a lamp by any observer. Also, they decided to make them white, so the green of the moss pots would become the table visual centre of the attention, encouraging people to focus on the technology.

The designers commissioned the manufacturing of the moss table to external professional model makers and concluded the design of the moss pots (point 18 on the map). While the table was being manufactured, the designers with the help of the scientist finished developing, refining and testing a prototype of the moss pot (numbers 19 and 20 on the map). Once its energy production was satisfactory, and after the designers had completed the design of the connection to the table elements, they engaged the technicians of their department for the production of the units needed for the table (point 21 on the map).

Picture 7.38 *The moss table during fabrication*

With the construction of the table on track, the designers and the scientist focused their attention on finding additional funding to exhibit it during the London Design Week. With this in mind, they made a presentation to senior scientists from the departments involved in BPV research (point 22 on the map). The scientists found the idea of presenting the result of their research in a context very different to what they were used to, intriguing and exiting; and conveniently, it suited their funding bodies' requirement for public dissemination of their research. The scientists also appreciated the aesthetic quality of the table and the way in which it demonstrated the potential of BPV technology. For all these reasons, they agreed to finance the exhibition of the table in the London design Festival. After this, the designers found an appropriated exhibition venue and designed the moss table exhibition stand.

Even though the moss pots would not be powering the table's lamp, they would still be generating energy. The designers wanted to communicate this during the exhibition, and make the table's production of energy tangible to people. They considered projecting on the exhibition wall a live interactive representation of the electricity generated by the moss. To do this, they devised a way of connecting the table to a processor that would transform the electrical signal coming from the table into a digital signal and send it to a computer. In doing this, the fluctuation of the electricity would control a flow of animated coloured bubbles.

The fabrication of the table was completed successfully and it was taken to the exhibition in London and assembled by the designers and the scientist (point 23 on the map). The moss table attracted significant interest from the design press, and especially from people working in sustainability.

Picture 7.39 *The moss table prototype*

Even though the case study formally concluded after the London Design Festival exhibition, the scientist and the designers continue the collaboration to take the table to Milan and they are now talking about continuing the collaboration, working on projects with industrialists and investors using and developing photovoltaic technology (point 24 on the map).

Picture 7.40 *Opening of the moss table exhibition at Designersblock in London*

7.8.3 Collaboration Output/Outcome

The photovoltaic collaboration had several outputs. One of the initial outputs was the graphic visualisation of the scientists' biophotovoltaics prototype. This visualisation served as the base for others made by the scientist to illustrate the findings of his research. Another output was the visualisation of future potential applications of biophotovoltaics technology. This visualisation was the main element for the design of the explanatory poster of biophotovoltaics technology exhibited at a public science event in London. Another output was the development and construction of a working prototype of an algae solar cell. From this prototype the scientist was able to prove a hypothesis about water as a by-product of biophotovoltaics processes. Also, the development of this prototype helped to improve knowledge about biophotovoltaics technology energy production efficiency in relation to the areas covered by photosynthetic organisms. Additionally, the collaboration allowed several versions of moss pots to be prototyped and tested. Graphic visualisation of these moss pots configurations was also made, aiding the scientist to visually explain details of his research. The final output of the collaboration was the prototype of the moss table. The moss table is a conceptual object intended to communicate the potential of biophotovoltaics technology to a non-scientific population. Alongside the moss table, another output was the design and making of an exhibition stand to present biophotovoltaics technology (and the moss table) to wider audiences in design trade fairs.

This chapter has presented an account of 3 exploratory and 2 development case studies, undertaken to provide evidence for the understanding of collaboration between designers and scientist in the context of scientific research. The description of each case study has explained the origin and development of the collaboration, how the design process occurred and what the collaboration output was. The following chapter will present the results of the analysis of these case studies underpinned by the analysis framework developed in the initial chapters of this thesis.

8. FINDINGS

Since this research examines collaboration phenomena in scientific research, section 8.1 of this chapter starts by explaining the positioning of the case studies in relation to the process of scientific research, showing how they range from its early to late stages. This is illustrated by mapping them in the scientific research process diagram developed in Chapter 5 (*Nature of scientific research*).

Underpinned by the model for collaboration between designers and scientists proposed in Chapter 6, section 8.2 comments on how engagement between designers and scientists happens during collaboration. It explains how the levels of integration between designers and scientists, the control that designers have over the project, and the nature of the activity undertaken by the designers have a strong influence on the different ways in which designers and scientists can engage in collaboration. Accordingly, each case study is presented with the help of diagrams to show how the designers and scientists engaged. The chapter also explains how the case studies revealed that the collaboration model proposed in Chapter 6 is not completely suited to illustrating the possible ways of collaboration between designers and scientists. The chapter argues that this happens because a) higher levels of engagement are determined by early involvement of designers in the definition of the design opportunities and problem identification, and not necessarily by the integration of the designer as a researcher as suggested in the initial model, b) the designer's focus activity has a wider scope than was suggested in the model of Chapter 6. Drawing on these arguments this chapter presents a revised model that addresses these issues.

Simultaneously, it also illustrates how the case studies are positioned within this new model.

This is followed by a presentation of findings on the role that designers can play in scientific research in section 8.3. Here the chapter argues that in addition to what is already known designers can play useful roles in scientific research, especially in helping to relate scientific work with society and industry, visualising and communicating science and connecting scientists' work with the world of design. In order to do this, the chapter discusses the case studies using the two different designer "role" models presented in Chapter 4. The first model helps to examine the apparent disconnection between the stage of scientific research at which designers intervene and the role they play. The second model (role-task) serves as a point of reference to identify previously unknown roles of designers collaborating in scientific research. This is then followed by a detailed explanation of the designer's role in each of the case studies, finishing with a summary list of these roles, plus the previously known roles identified in Chapter 2.

Section 8.4 discusses the case study results in relation to the nature of designer contribution to scientific research. It explains how the case studies have revealed new types of contribution to collaborative effort with scientists. It presents the contributions made in each of the case studies, illustrated with examples. This is followed by a summary of the new contributions, showing that designers can contribute in eight main areas within scientific research. The list demonstrates that most of these areas are composed of a mixture of old and newly evidenced contributions, with one exception which is composed only of new contributions: the area of commercialisation of scientific research. The section also introduces how designer contribution affects all the three dimensions of scientific research. This is further explained in section 8.6 of this chapter.

Section 8.5 discusses the research findings on barriers to and enablers of collaboration between designers and scientists. The section offers a detailed identification of barriers to and enablers of each of the case studies. This is summarised and concluded with comparative tables of barriers and enablers. These tables integrate newly found barriers and enablers from the case studies with the barriers and enablers identified in Chapters 1 and 6. The section reveals three main aspects of collaboration that are a main source of barriers: the collaboration settings (especially regarding time management), the personal characteristics and attitudes of collaborators, and communication issues. The section also shows enablers that have not been previously identified in other studies. These enablers have been grouped in two clusters: the collaboration process and resources.

Section 8.6 explains how contributions and role-tasks previously identified from the case studies have an impact on specific activities of scientific research. To illustrate how this happens, contributions and role-tasks are mapped onto diagrams of the three scientific research dimensions. These maps evidence the occurrence of role-tasks and contributions to scientific activity, demonstrating how design can impact all dimensions of scientific research. This section also demonstrates that design intervention has a greater impact on scientific research (especially in is social and rational dimension) if occurring at either an early or a late stage.

This chapter ends with a summary and explanation of the implications for the study, including a short introduction to this thesis's conclusions.

8.1 Positioning the case studies

As explained in Chapter 5, applied research is driven by considerations about use and applications. It is possible that designers find natural ways to contribute to this type of research, since usability is one of designers' key areas of knowledge and expertise. In contrast, designers might be expected to make less contribution to basic research, where there is little concern for application and use, and all activity is centred in trying to understand basic scientific phenomena. For this reason it is important to describe science as a staged process, so that design influence can be associated with specific stages from basic to applied.

In order to position the case studies, this chapter will use the scientific research process model developed from Stokes and the OMEC model in Chapter 5. This model helps to position collaborative effort within the scientific process and also inside the adjacent boundaries of application development. Although science is an iterative process, an underlining principle of progression from basic research to applied research (and then to application development) implies a sequence in which there is a beginning and an end, and where there are both early and late stages in that process. According to this, early stages are associated with basic research while later stages are associated with applied research and to the development of applications.

To show the position of the case studies, icons representing the research are placed in a diagram of the model's relevant area of research. These icons indicate the type (and stage) of research undertaken by the scientists. If two or more icons are placed in different places, this means that several types of research are happening simultaneously. Also, arrow lines joining the icons represent the research direction intention preceding the collaboration, and dotted arrow lines represent the research direction after the collaboration. These arrow lines show if the research is moving towards a different stage, and to which one it is heading.

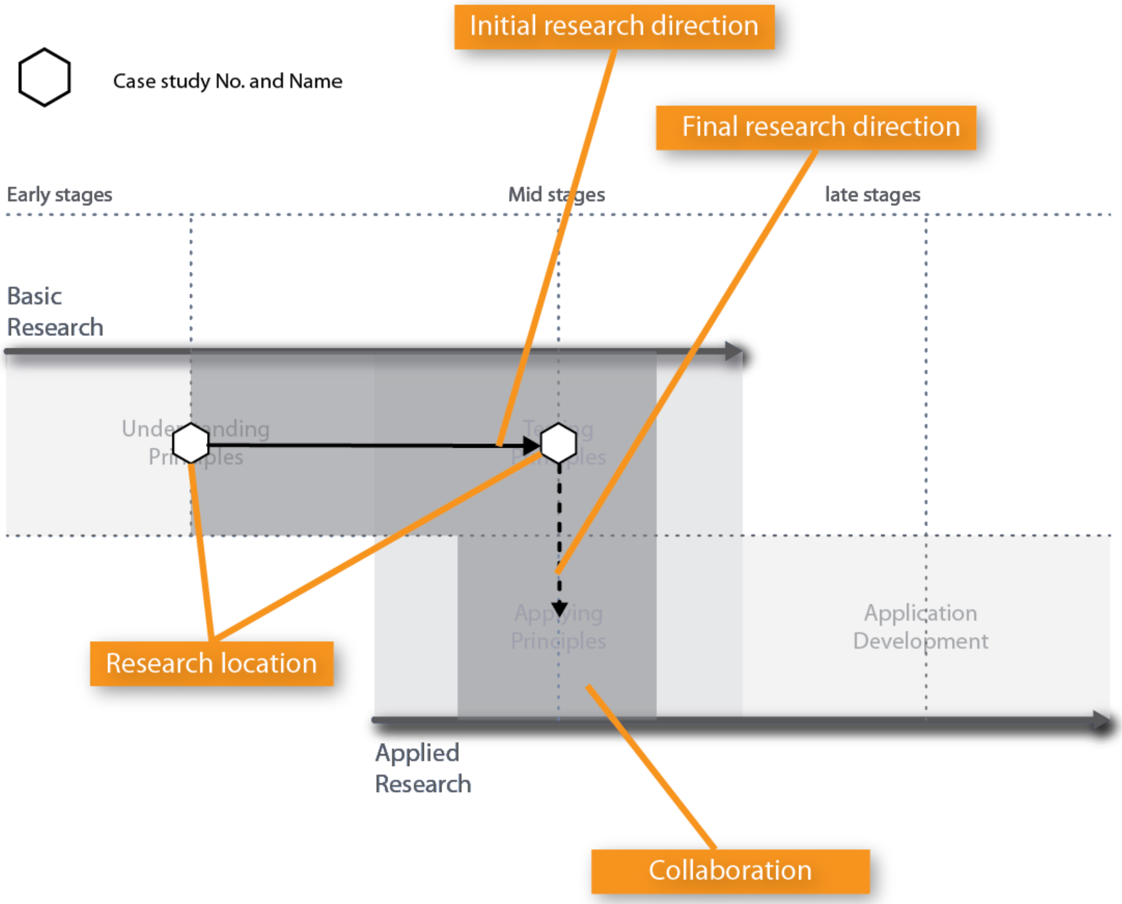


Diagram 8.1 *Explanation of the case study positioning diagram*

8.1.1 Positioning case study 1: Mask collaboration

The scientist was researching oxygen therapy, aiming to understand the therapeutic effects of controlled administration of gases to patients with respiratory problems. At this stage the scientist was conducting basic research, since its purpose was to understand the principles that govern the effects of oxygen therapy on patients.

To confirm or disprove his hypotheses related to oxygen therapy, the scientist created a device (the mask) to administer gases to patients in a controlled fashion. In this context the mask was an experimental device. However, as oxygen therapy can be only administered with a device (mask), research on the mask and its sealing principle became an integral part of his oxygen therapy research. This shifted the research from basic to applied since it sought the application of a principle (the one governing the effects of oxygen therapy on patients) to an application (a mask to administer oxygen therapy).

Moreover, in addition to his scientific purposes, the scientist was intending to further develop the mask as a commercial product, as he foresaw a potential market for it in hospitals and health centres. For this reason, he was planning to produce a batch of masks to conduct medical trials in order to validate the mask's effectiveness as a device for oxygen therapy. Then he would seek an industrial/commercial partner to manufacture and sell the mask. In this way, his research would move outside the realm of science towards application development in the commercial world.

To sum up this case, the collaboration started while the scientist was conducting basic research (trying to test principles). Later the collaboration continued while the research became applied research (applying principles to a device) moving in this way towards its middle stages. In the end the collaboration did not reach the late stages of the research (application development) even though it was intended to, because the scientist left the research project for a new job in a different university.

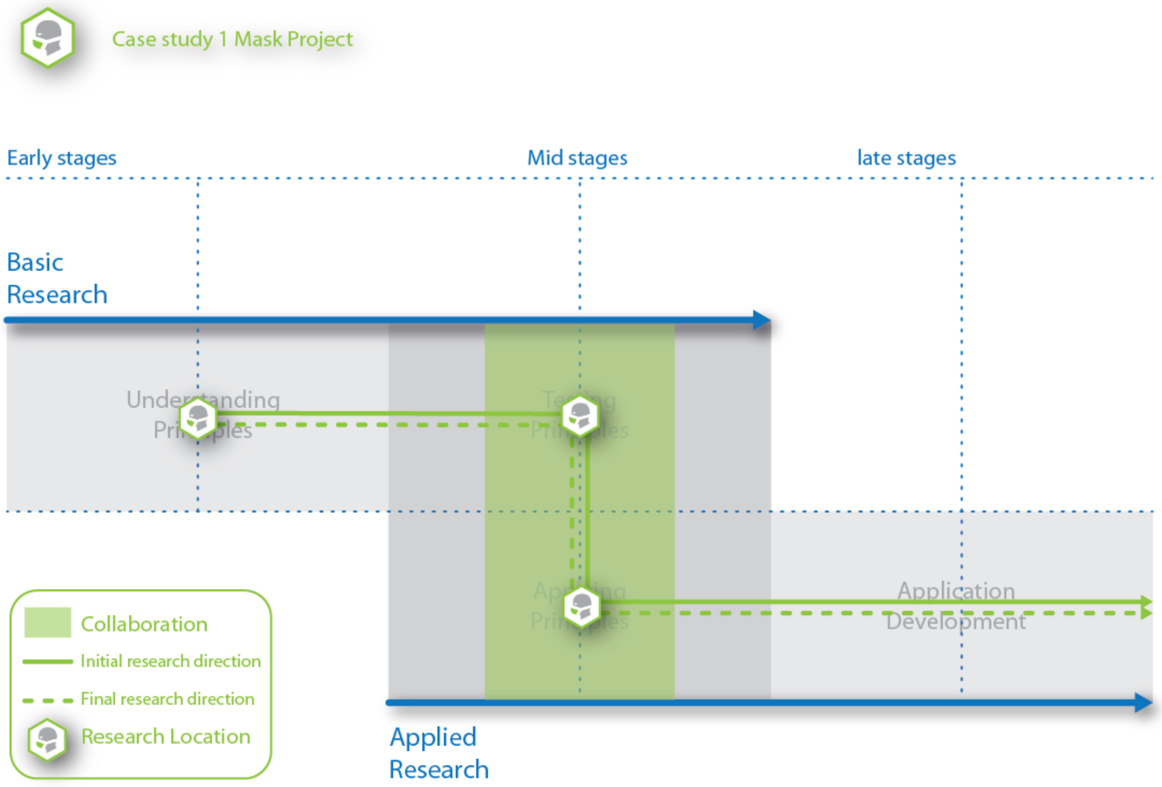


Diagram 8.2 *Position of case study 1 (Mask) in the scientific research process*

8.1.2 Positioning case study 2: Immunoassay collaboration

The scientists were using a special material (MCF) to build a piece of equipment for experimentation (a device to purify proteins), when they “accidentally” came up with the idea of using the same material to build another device to conduct Immunoassays in a new safer and more efficient fashion. They focused their attention on manufacturing a model of the device in order to prove their idea and pursue the development of the device as commercial product. Although their idea came from basic research activity, this development became a clear example of applied research. This is because the scientists were intending to apply a series of tested principles (MCF capacity for retaining reactive substances on its internal capillaries) on the development of an application (a device for conducting immunoassays). So this collaboration started during the middle stages of the research and ended in the late stages, when the device was ready to be further developed as a commercial product.

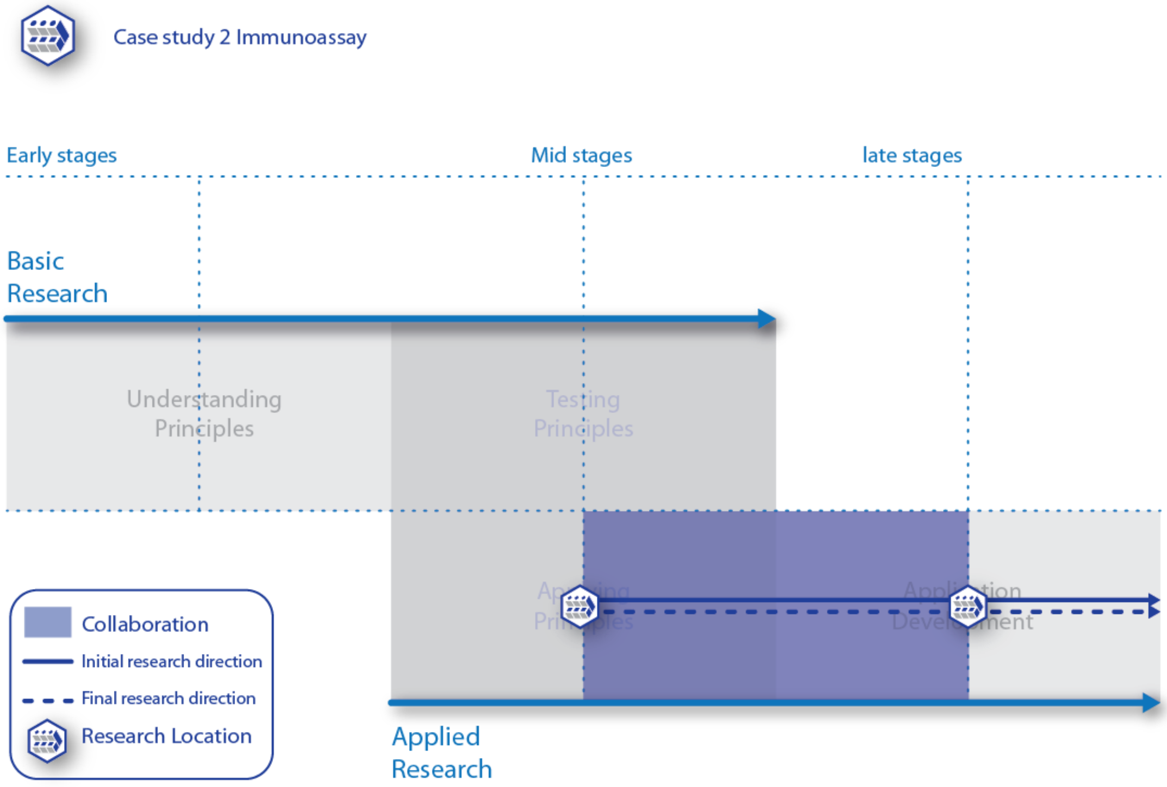


Diagram 8.3 *Position of case study 2 (Immunoassay) in the scientific research process*

8.1.3 Positioning case study 3: Multistable collaboration

The scientist had a patent for a forming process that confers bi- and multistable properties to metal sheets. He was seeking to attract commercial interest in his forming process from entrepreneurs and industrialists. For this purpose he developed several application concepts using bistable materials generated from his patented process, and showed them to possible investors. One industrialist took interest in one of them, a hinge for a wearable accessory using a bistable material. From this point, his research shifted towards the further development of this application. This research can be placed in the middle stages of scientific research, geared towards application development.

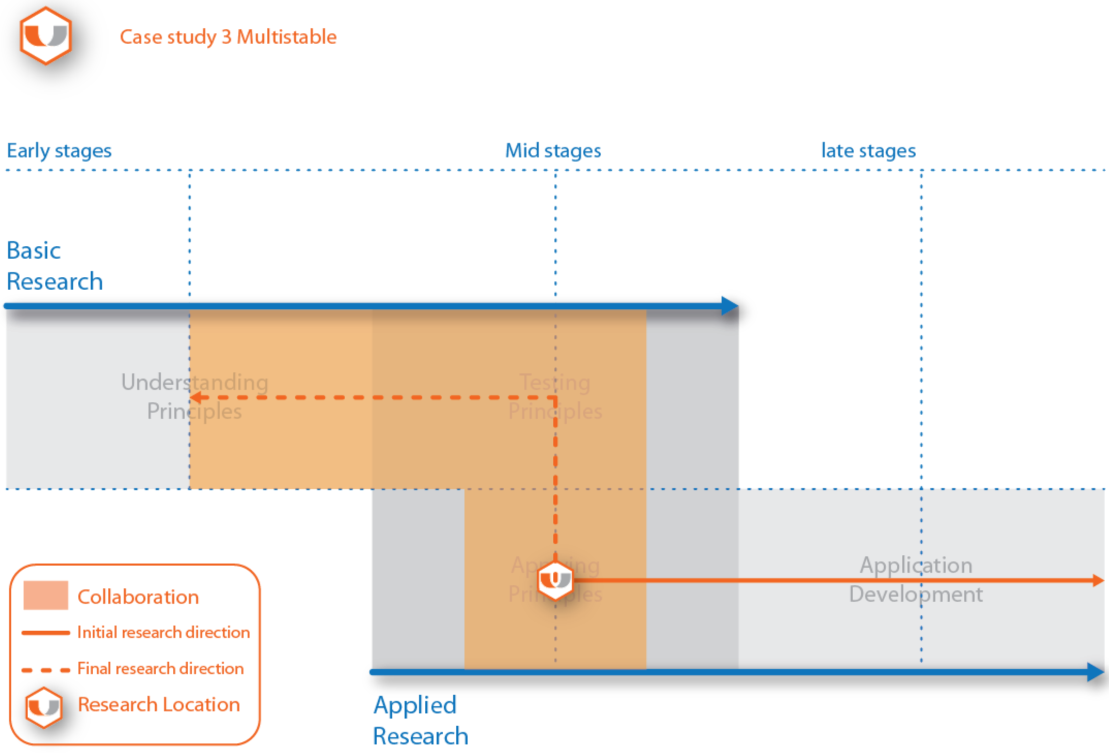


Diagram 8.4 *Position of case study 3 (Multistable) in the scientific research process*

In this case, the collaboration started during the middle stages of the research (applied research) but it did not move in the expected direction towards application development. On the contrary, it pushed the research towards the development of further basic research, when the design team made evident some gaps in the understanding of the technology.

8.1.4 Positioning case study 4: Stem Cell collaboration

The scientists were conducting research on the generation of pancreatic and hepatic cells from human stem cells, focusing on the understanding of the cell differentiation processes and on how stem cells respond to their environment. Although it was expected that the outcomes of this research would be applied in the future to regenerative medicine for the diagnosis and treatment of illnesses, the research was still in its early stages, focused on the understanding of principles. The collaboration started and finished during this stage and did not have any noticeable effect on its direction.

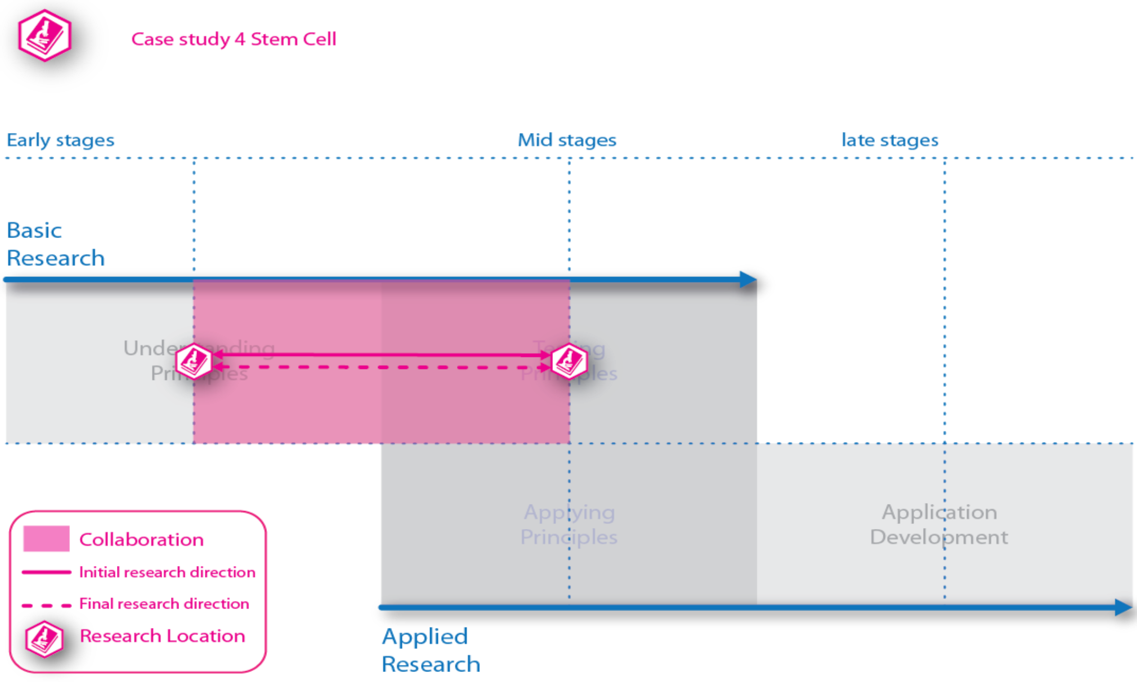


Diagram 8.5 *Position of case study 4 (Stem Cell) in the scientific research process*

8.1.5 Positioning case study 5: Biophotovoltaics collaboration

The scientists’ research was focused on understanding the chemical and biological mechanisms by which photosynthetic processes of living organisms can generate electric energy. In order to study these phenomena, the scientists created an experimental prototype to enable them to obtain data to support their theoretical development and publish their findings. This created the base for a new technology called Biophotovoltaics. Up to this point the scientists were conducting basic research since they were only trying to understand and test principles, without any application in mind. It was research in its early stages.

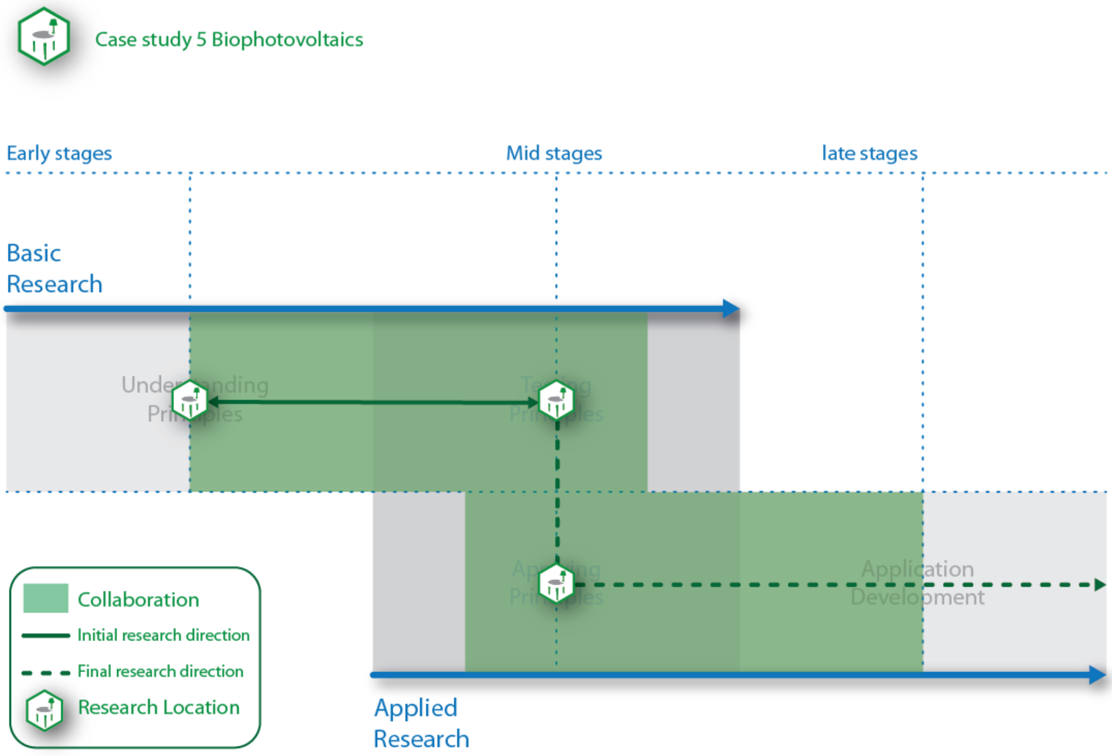
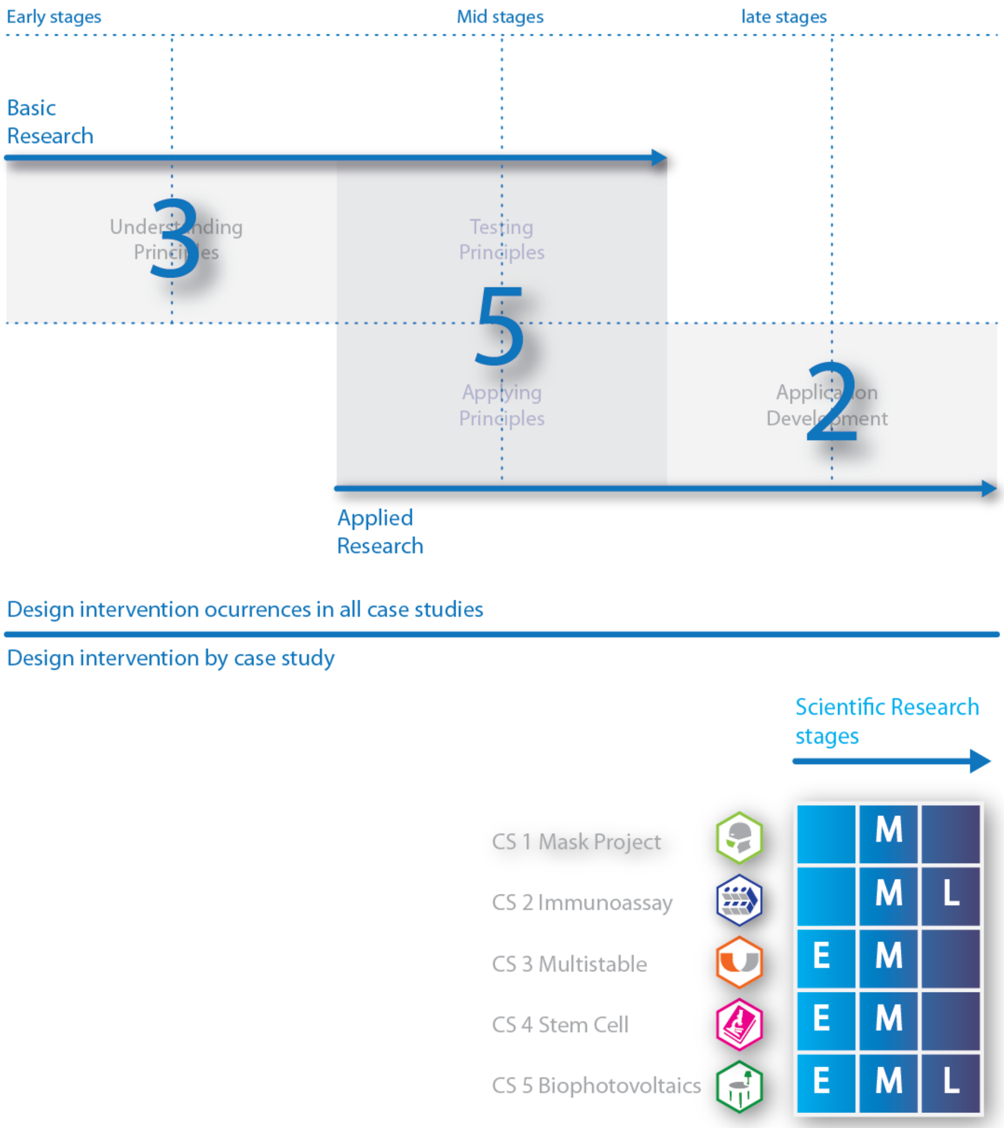


Diagram 8.6 *positioning of case study 5 (Biophotovoltaics) in the scientific research process*

The collaboration started when scientists engaged with designers to develop communication material about their research for a science fair. At this point the designers suggested visualising possible future applications of the technology, in order to communicate it more effectively. This eventually led the team to focus their activity on the development of a conceptual object (the moss table) incorporating Biophotovoltaics technology as a means of disseminating the technology in non-scientific circles. This triggered a shift in research activity towards applied research, since it was focused on the application of principles. At this moment the research was in its middle stages. The moss table was exhibited in design trade fairs and attracted the attention of investors interested in both the table and the technology. This opened up a potential route for the possible commercialisation of the technology. Thus, in its late stages, the focus of the research became open, with the possibility of application development. However this means neither that basic research activities stopped or that a substantial part of the research effort remained fixed on basic scientific and technological research. It is just that the collaboration triggered simultaneous research activity at all stages.

8.1.6 Design activity and the positioning of case studies

After positioning the case studies it can be concluded that designers have the potential to contribute at all stages of scientific research, regardless of whether or not the research is basic or applied. As illustrated in Diagram 8.7, there is scope for designer contribution in the early stages of non-applied research, as much as in applied research. The diagram showing the design occurrences of all case studies indicates a major concentration of design activity in the middle stages of scientific research. However this can only be related to the particular choice of case studies, rather than to a natural tendency of design collaboration to happen in these middle stages. However, it may be possible that such a concentration is the result of design activity moving from the early and late stages towards the middle stages and vice versa. This connects with the observation that design intervention in each case study happened in at least two stages of the scientific research. It may be the case that design intervention either fosters research transition between stages, or that its own nature makes it move between stages. In any case, it seems that design intervention can move between stages.



CS 1 Mask Project		M	
CS 2 Immunoassay		M	L
CS 3 Multistable	E	M	
CS 4 Stem Cell	E	M	
CS 5 Biophotovoltaics	E	M	L

Diagram 8.7 *Summary of design intervention in the case studies*

8.2 What different forms of collaboration can take place between designers and scientists?

As illustrated in Chapter 6, collaboration between designers and scientists takes place in different forms, progressing from low levels of engagement towards higher levels. This progression is determined by three main aspects: integration, project control and nature of activity. Chapter 6 proposed a model of research engagement for designers and scientists that serves to categorise designers' engagement with scientists in scientific research according to possible variations in these 3 categories. The initial model suggests 4 levels of research engagement. The lower level classifies the designer as a design supplier. The second level classifies the designer as a team member. A third level identifies the designer as an embedded designer. Last, the fourth level categorises the designer as a team researcher.

This section examines the case studies to determine how they fit in the model proposed in Chapter 6. Furthermore, the section demonstrates that Chapter 6's model did not entirely explain how designers and scientists engaged in collaboration in the case studies, and outlines an improved model. In order to do so, section 8.2 examines each case study under the three main aspects of integration, project control and nature of activity developed in Chapter 6. To look at integration, diagrams of activities have been drawn to help visualise the level of integration between designers and scientists during collaboration. These diagrams are based on the collaboration matrixes that accompany each of the case study descriptions in Chapter 7.

As illustrated below (Diagram 8.8) each activity that took place during the case studies was classified in order to determine if it was undertaken individually by the designers or the scientists, or if it was a shared activity. Also, formal meeting points were registered. The diagrams also specify if the activities were related to scientific research or to design work. In this way, it is possible to observe and quantify the level of integration of designers and scientists by counting shared activities and comparing them with individual activities, and by looking at when designers and scientists are working across both scientific research and design work activity.

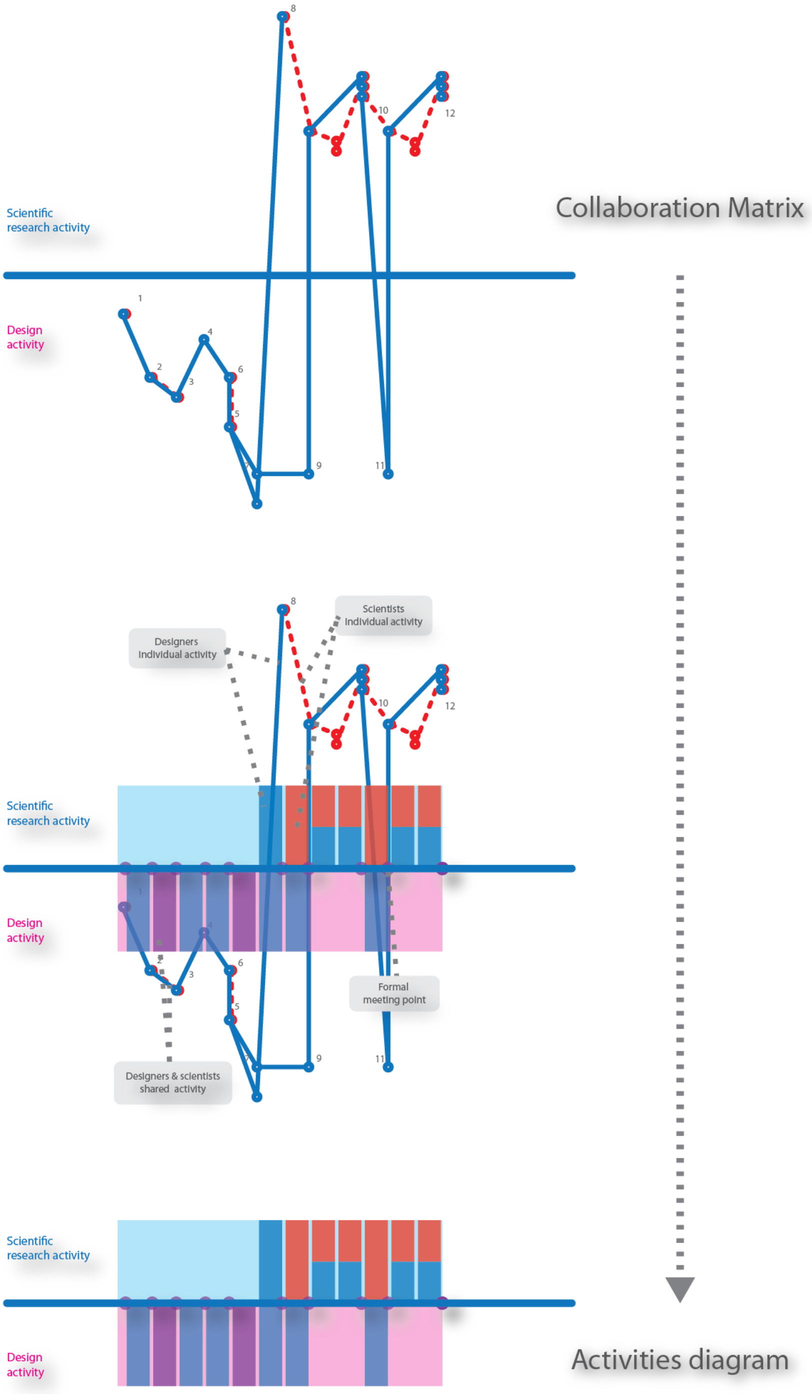


Diagram 8.8 *How the activities diagram has developed from the case study mappings on the collaboration matrix*

To examine project control, this section looks at how early on designers become involved in the identification of the issues to resolve, and in the formulation of conceptual solutions. To help with this, diagrams have been drawn showing three main points of reference, so the designer's project entry point can be located easily. The last aspect studied is the nature of the design activity. It describes the extent to which the design activity has focused on the resolution of issues directly related to the scientific enquiry or on the resources needed to conduct scientific research.

8.2.1 How designers and scientists collaborated in the Mask case study:

Integration

In the mask collaboration there was a relatively low level of integration between designers and scientists. As seen in Diagram 8.9 designers and scientists rarely developed activities together, either research or design related. Mutual interaction and sharing of ideas was mostly limited to their presentation meetings.

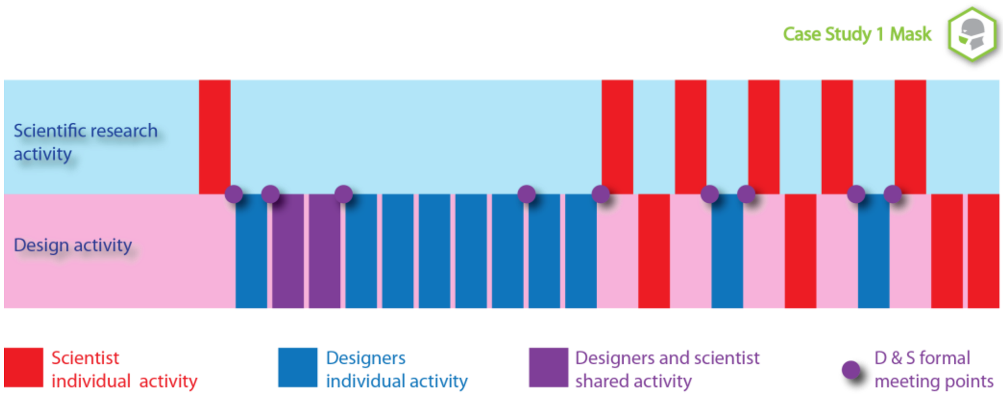


Diagram 8.9 *Mask project activities diagram*

Unlike the other case studies, the scientist did not take part in the initial ideas brainstorm at the beginning of the project. This may have hindered the scientist's integration in further stages of the project, preventing him from directly observing (and perhaps understanding) the way in which designers operate. Also, for ethical reasons, the designers were not able to take part in their own design-testing on users (cadavers and patients). This prevented potentially valuable interaction with the scientist on design aspects of the project while testing was carried out and caused them to miss team-building opportunities.

It is also noticeable that while all the activities undertaken by the designers were design- and not science-related, the scientist moved across towards design activity on some occasions, especially after the designers fabricated their first prototype. As seen in chapter (interdisciplinary), highly integrated interdisciplinary teams tend to divide tasks according to criteria other than disciplinary differences, not as it occurred in this case study.

Last, the designers focused on a single project specified from the beginning and did not change that focus or move towards other issues during the collaboration. This shows a type of engagement typical of an external design supplier.

Project control

In the mask project the designers started collaborating when the project advanced beyond its first stages. By the time the designers got involved, not only was there a clear project scope definition (the development of a mask for experimental purposes with views on further developing it as a commercial product), but also a conceptual working principle (the sealing principle) was already established as well as a first working prototype. It is noteworthy that the designers decided to use their first brainstorm session to look for alternative sealing principles that had not been explored by the scientist. That can be interpreted as a move by the designers to gain control of the project. Diagram 8.10 shows the designers' entry point in the project.

Mask project

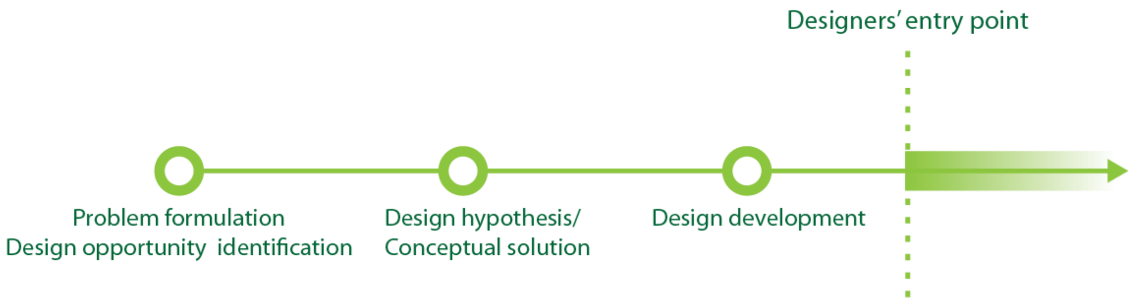


Diagram 8.10 *Mask project designers' entry point*

Nature of activity

The designers' activity in the mask project was geared towards issues related to the resources needed to conduct scientific research. The mask's original concept was to be a device to conduct experimental work underpinning research into oxygen therapy. Later, however, the mask became the focus of the research, which then became applied instead of basic. Because of this, the scientific principles underpinning the mask's functionality (sealing principles) became part of the scientific research. The designers, through the development of their mask design ideas, developed empirical evidence that helped the scientist to improve understanding of his sealing principle and the designers to improve the design of their mask. Indeed, the sealing principles initially presented by the scientist were later found to be insufficient. If the design team had not challenged these, then the real nature of these principles would not have been identified. However, the focus of the designers' activity was still on the design aspects of the mask as a functional object, and not only on understanding the sealing principles. This shows how disciplinary roles were maintained.

It can be concluded that during the collaboration the designers acted essentially as external design providers, became involved in the project at a late stage and focused their efforts principally on the development of scientific resources. However they also dealt with issues directly related to scientific enquiry (e.g. the sealing principle). In this way the collaboration matches the Level 1 Design Supplier according to the model of research engagement in Chapter 6.

8.2.2 How designers and scientists collaborated in the Immunoassay case study:

Integration

In the immunoassay collaboration the designers acted as external design collaborators and remained separate members of the research team during the whole case study. Although there was substantial shared activity between designers and scientists, as seen in Diagram 8.11, it was mainly focused on the project predetermined at the beginning of the collaboration (immunoassay device). Also, all of the designers’ and scientists' shared work was in design activity and none in scientific activity. In only one instance did the designers work on scientific research activity by contributing to the scientists’ written funding proposal.

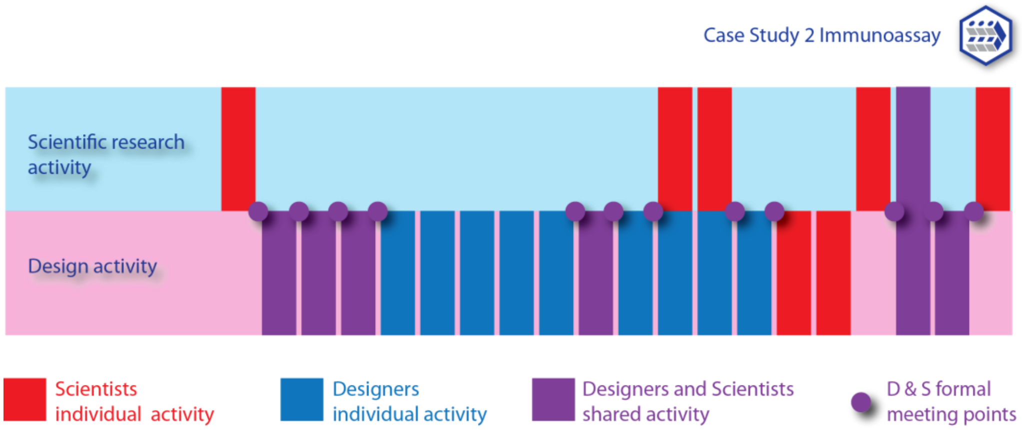


Diagram 8.11 *Immunoassay project activities diagram*

Project Control

As was the case with the mask project, by the time the collaboration began, the design project had already started. In effect the scientists had already outlined the project aim, which was to design an improved version of a device they had already prototyped so that their idea for a new method to conduct immunoassay could be developed and tested. This had the additional purpose of setting the foundations for the further development of a commercial version. Although the scientists had a clear idea of the physical and chemical principles governing the functioning of their prototype and its technical requirements, at that moment they had not identified other key design aspects of the device related to safety, handling and compatibility with other laboratory instruments. The designers helped to identify those issues and, in doing so, they reformulated the problem and played a major part in the generation of the design hypothesis/conceptual solution. Because of this, it can be considered that the designers entered into the project earlier rather than later, as illustrated in Diagram 8.12.

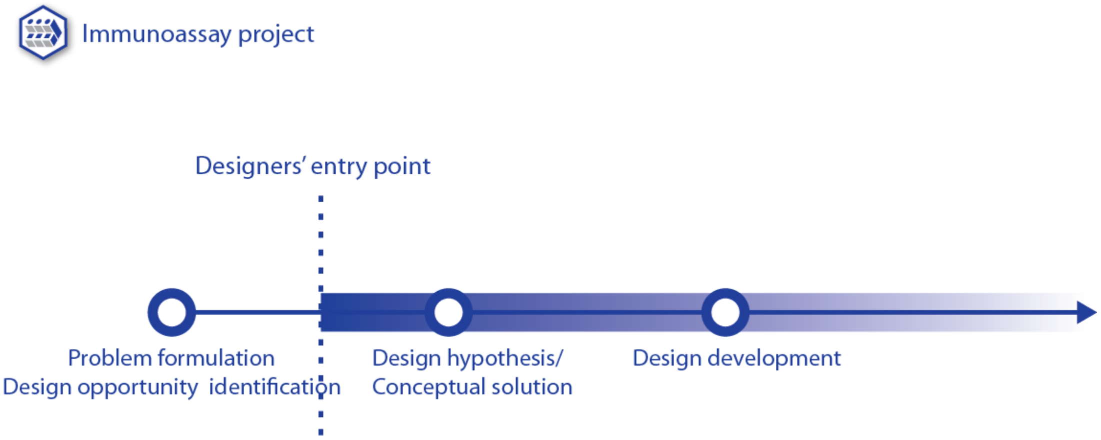


Diagram 8.12 *Immunoassay project designers' entry point*

Nature of activity

In the immunoassay case study, the scientists were conducting applied research. Their research was looking for the development of a device that provided an efficient way of conducting a standard laboratory technique (Immunoassay) using a commercially available component. In this case study, the nature of the design activity was ambiguous. On the one hand it was directed towards the resources needed to conduct scientific research, being about designing a resource needed to undertake scientific research. On the other, it focused on the scientific enquiry, since the development of the device was both the purpose of the research and the design activity. Nevertheless, the designers concentrated on the development of the device as a functional object, while the scientists focused on understanding the chemical and physical principles that made it work. Both designers and scientists kept their disciplinary identities during the project, even if the scientists had an active role in design brainstorms carried out informally during presentation sessions.

In short, the designers' level of integration was external, they had an earlier entry into the project, and the nature of their activity was dual, focusing on both the resources for research and the issues related to the scientific enquiry. It is noticeable that this pattern does not coincide with any of the categories in Chapter 6's model of research engagement.

8.2.3 How designers and scientists collaborated in the Multistable case study:

Integration

In the Multistable case study the designers acted as external design suppliers and remained separated from the research team. This case study showed very low levels of integration between designers and scientists. As seen in Diagram 8.13, there was no interaction between the collaborators other than the set formal meetings. The fact that the collaboration did not reach the design stages and ended before a concept design solution was formulated might explain this lack of integration.

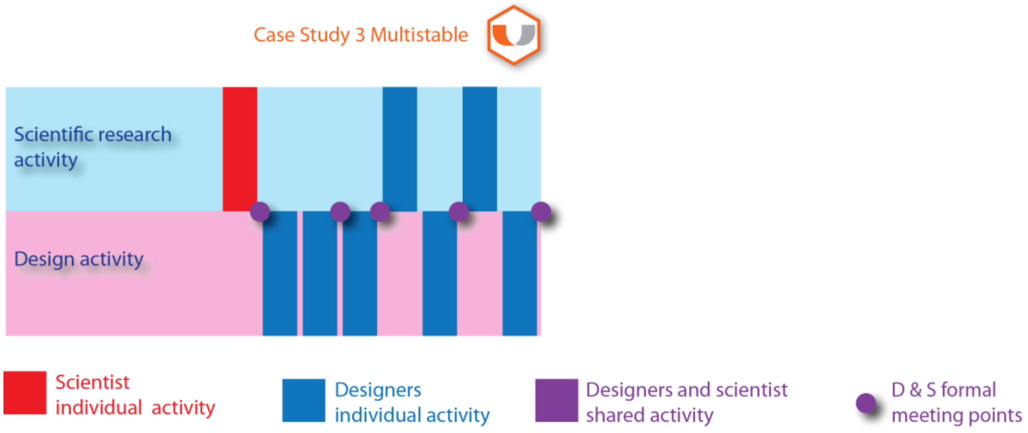


Diagram 8.13 *Multistable project activities*

Project control

In the multistable project the designers made a relatively early entry. By the time they started collaborating, the scientist already had a clear idea of the design challenge, which was to develop a hinge for a wearable accessory. However he did not have a definite sense of how this could be achieved. It was set as the designers’ job to develop a design conceptual solution and to develop it. Eventually the designers realised that before they were able to deliver this, they needed to gain more scientific knowledge about the multistable forming process. By identifying this lack of knowledge, the designers outlined an inherent problem in the way in which the design problem had been outlined. By doing so, they pushed back the design project to its pre-problem formulation stage.

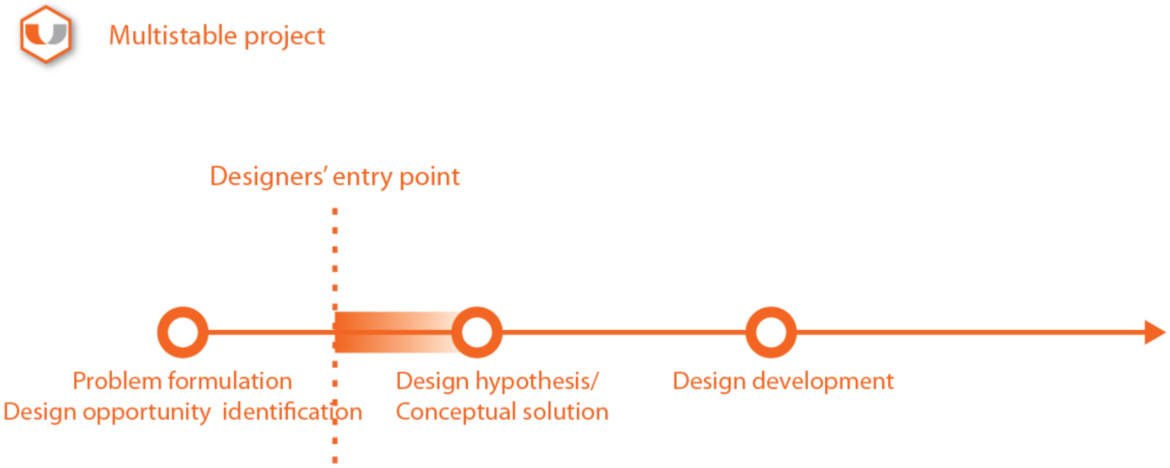


Diagram 8.14 *Multistable project designers’ entry point*

Nature of activity

In the Multistable project, the scientist was conducting applied research geared towards the development of applications, as well as basic research with no application in mind. The designers’ activity was intended to focus on the development of an application originally conceived by the scientists (a hinge for a wearable accessory) as part of their applied research activity. For this reason the designers' activity was centred neither on resources to conduct scientific research nor on issues directly related to scientific enquiry. In this case, design activity relates to the commercial dimension of scientific activity.

In brief, the designers in the multistable collaboration acted as external designers, they entered the project early on and their activity was focused on the commercial dimension of scientific research. Like the immunoassay collaboration, the multistable collaboration does not exactly match any of the categories in Chapter 6's model of research engagement.

8.2.4 How designers and scientists collaborated in the Stem Cell case study:

Integration

In the stem cell project the designers acted as external designers and achieved only a low level of integration within the research team, possibly because a design need was not originally identified by the scientists. Because of this the scientists took a passive/collaborative role in this collaboration and let most integration-fostering initiatives such laboratory visits and shadowing be generated by the designers. This may have prevented more integration. In spite of this, there were several instances of shared activities as seen in Diagram 8.15, as well as frequent feedback meetings.

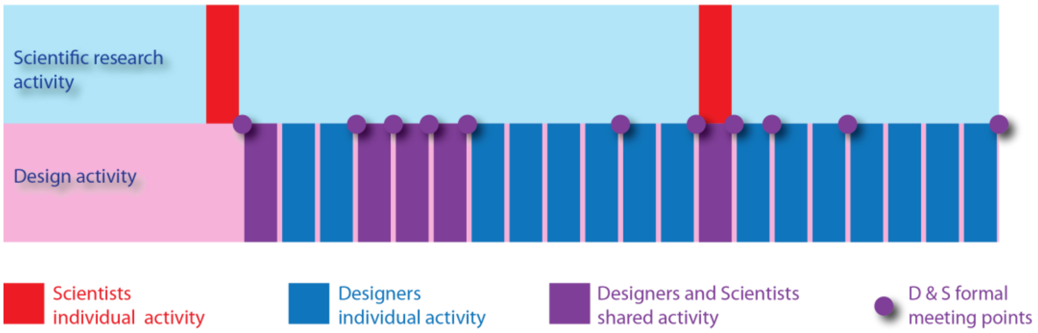


Diagram 8.15 *Stem Cell project activities*

Project control

The stem cell case study was the only one in which the designers had complete control of the project. It was their task to find the design opportunities, to formulate the design hypothesis and to develop the initial design concept. Although this offered advantages to the design team, such as being able to choose the design issue they found most useful and interesting, it had some disadvantages. For instance, they did not have the insight into design opportunities that they had in other case studies in which the scientists had identified them. Also they had to be more cautious while identifying design issues to avoid giving the scientists the impression that they were being criticised.

Stem Cell project

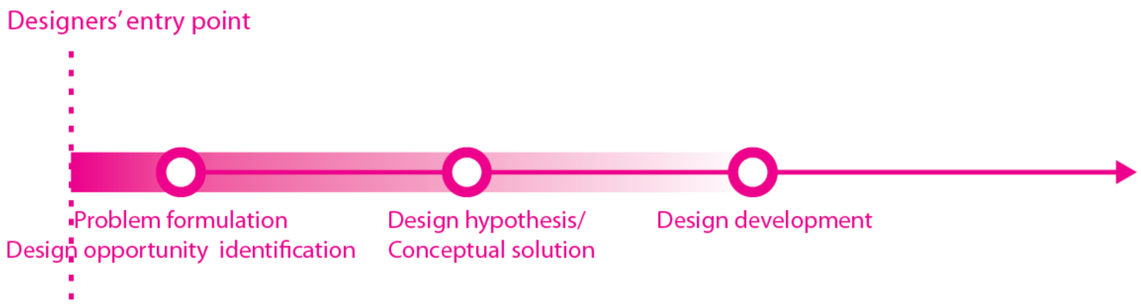


Diagram 8.16 *Stem cell project designers' entry point*

Nature of Activity

In the Stem Cell case study the designers did not look at the resources needed to conduct scientific research or at the issues directly related to scientific enquiry. Instead, after considering several design opportunities, they chose to look at the way in which scientists interact and communicate. This created a distinction from the other case studies in which the design focus fell into one of the two areas mentioned above. It also shows a new area of work that was not included in the model of collaboration proposed in Chapter 6. As a design response to issues in the area of communication the designers proposed an interactive laboratory book. This solution can ultimately be considered a “resource” needed to conduct scientific research, although the focus of the case study was communication. In any case, the designers kept their disciplinary identity, as their work was not focused on the scientific enquiry.

To sum up, in the Stem Cell collaboration the designers' level of integration was external. They made a very early entry into the project and their activities focused on the communication and interaction of scientists conducting scientific research (although their response was to design a resource for conducting scientific research). It seems that as in the Immunoassay and the Multistable case studies, the Stem Cell case study does not match any of the levels proposed in Chapter 6's model of research engagement.

8.2.5 How designers and scientists collaborated in the Biophotovoltaics case study:

Integration

The integration between designers and scientists evolved during the project. When the collaboration started, the designers acted as external design providers. Nonetheless the integration started to change from the beginning of the collaboration, when the scientists got involved in design activity by participating in the initial brainstorm session. This involvement gave the scientists a glimpse of the designers' working methods and to both scientists and designers the opportunity to start operating as a working team. Later on, when some prototypes developed by the designers were tested, the designers had the opportunity to work alongside with the scientists in their lab. They even performed some scientific tests on the prototypes.

The designers completed their original task (the visualisation of future Biophotovoltaic application concepts and the design and fabrication of a Biophotovoltaic algae demonstrator) and the scientist expressed their satisfaction with it. The collaboration was then extended and they teamed up with one of the scientists to develop one of the future application concepts they had created: the moss table. At this stage, designers and scientist became part of a single team, and the designers turned into internal rather than external design suppliers.

As seen in Diagram 8.17, as soon as the collaboration was extended (marked on the diagram with the purple dotted line) the designers and the scientist engaged in shared activities on scientific research and on design. It is worth highlighting the high frequency and regularity of meeting points during the collaboration compared with the other case studies. For example, in the Stem cell project there were 11 meeting points for 21 activities. This is a ratio of 0.5 meetings per activity. In contrast the Biophotovoltaic project had 21 meetings for 27 activities, giving a higher ratio of 0.7 meetings per activity*. This high frequency of meetings, together with the involvement of both designers and scientists in shared scientific and design activities may have contributed to the progressive integration of designers and scientists into a single team.

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* Numerical comparisons should not be interpreted as experimental measures.

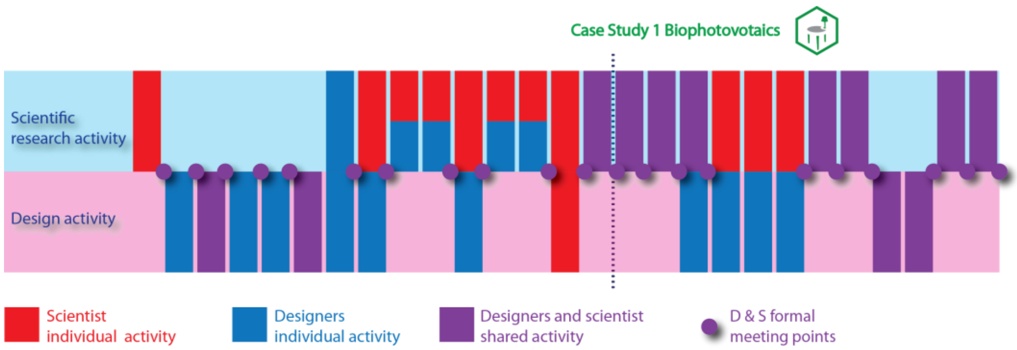

Diagram 8.17 *Biophotovoltaics project activities*

Project control

When the Biophotovoltaics collaboration started, the scientists had a clear idea of what the design issue was (they required a poster to communicate their research at a science exhibition in London). The designers started by outlining some conceptual design solutions (visualisation of future applications of the technology for the poster and a technology demonstrator that was visually attractive and that made explicit the way in which the technology worked) and then they proceeded to develop and implement them. From this it can be concluded that the designers entered the project at an early rather than a late stage. However when the collaboration was extended with a new project, the designers were involved at a very early stage, taking a leadership role in the design opportunity identification and the design of the conceptual solution. They then worked together with the scientist to develop it. These two different entry points can be seen in the next diagram.

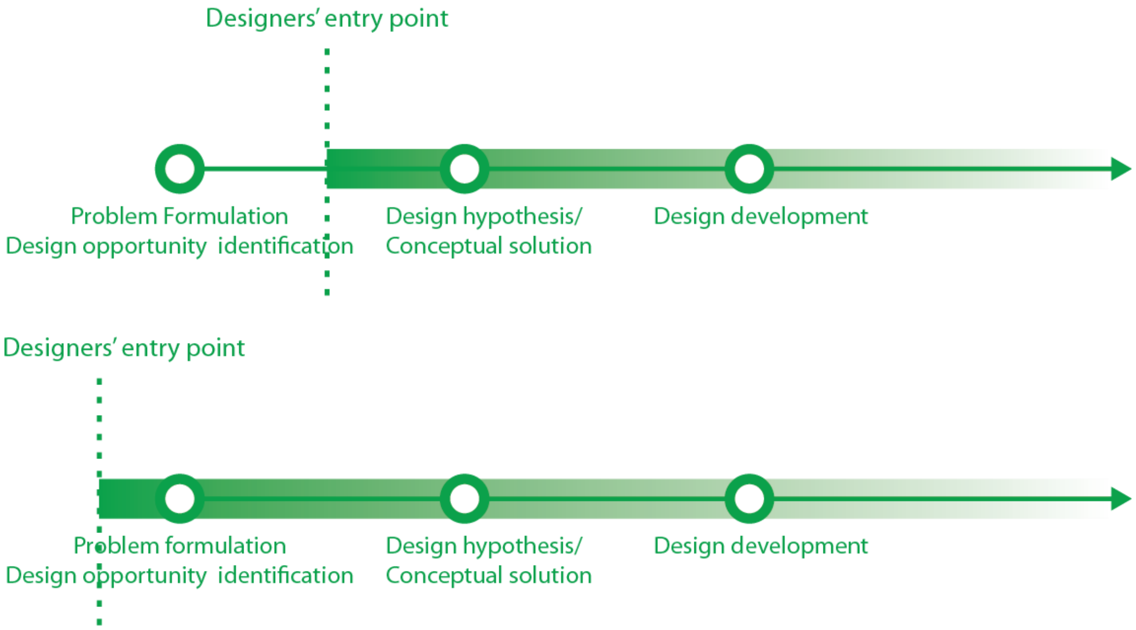

Diagram 8.18 *Biophotovoltaics project designers' entry points*

Nature of activity

In the Biophotovoltaics case study, the nature of the designers' activity changed during the project. When the collaboration started their focus was on the resources needed to conduct scientific research. They worked on the social dimension of scientific research, designing elements to communicate the scientists' research to wider audiences. When the projects shifted towards the development of the moss table, the focus of activity changed as well. Even though the project was still about communicating the technology, the designers teamed up with the scientist to optimise and develop the production of a device capable of producing a stable electrical current from moss. This was not any longer about communicating technology, but about developing the technology and researching materials and formal configurations to reach a fixed energy production goal. It became apparent that this activity moved from the social to the rational dimension of scientific research. While developing the "moss pots"[23] the designers and the scientist worked together, often discussing design and scientific aspects of the device. Even if eventually the designers and the scientists worked on the project most of the time within their own disciplinary boundaries, on some occasions, disciplinary boundaries were blurred.

To summarise, in the photovoltaic collaboration the designers' integration evolved from external to internal. Regarding project control, the designers had a relatively early entry into the project but as the collaboration extended, they had an early entry in the second stage as well. Last, in the same way as the integration evolved, the nature of the designers' activity also changed focus, from being only on the resources needed to conduct scientific research (in its social dimension) to encompassing issues related to scientific enquiry (in its rational dimension).

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[23] The moss pots are Biophotovoltaic devices in which energy is generated from the interaction between bacteria and moss. They are energy bio cells.

8.2.6 A collaboration model from the case studies

Examining all case studies together makes evident some discrepancies between them and the model developed in Chapter 6. First, It seems that progression towards higher levels of engagement is not necessarily led in the first instance by the integration of the designer as part of the design research, as was suggested in the Chapter 6 model. Instead, it its apparent that this progression is first characterised by the earlier involvement of the designer in the definition of the design opportunities and problem identification.

Secondly, the evidence suggests that the nature of the designers' activity in scientific research has a wider scope that that outlined in the Chapter 6 model. For example, the Multistable case study showed that designers can focus their activity on the development of scientific output towards commercial products. This demonstrates that designers' activities are not only related to the two areas identified in the model (resources needed to conduct scientific research or scientific enquiry). In a similar way, the Stem Cell case study made it obvious that there are other forms and areas of design activity that cannot be categorised in the way that the model in Chapter 6 does. Indeed, the area of communication between scientists cannot be categorised as a resource to conduct science or as a scientific enquiry.

Even though the evidence of the case studies shows discrepancies with the proposed model of collaboration, it also demonstrates that its 3 aspects (Integration, Project control and Nature of activity) are useful elements to differentiate and classify collaboration between designers and scientists. It also makes evident that although the model's intermediate levels do not reflect how collaboration happens in reality, the lower and higher levels of engagement actually do, as is noticeable in Diagram 8.19.

Based on these observations, a revised version of the model is proposed reflecting the forms of collaboration identified in the 5 case studies of this research. Instead of the 4 levels of engagement from the original model, the new one has 3. The first and the last level remain from the original, but the intermediate levels have been merged. In this new level, the designer remains as an external member of the research team, but his/her involvement in the identification of design problems/opportunities is greater (with early involvement in the project), which also means more control of the project. Also, the designer still does not work directly on matters of scientific enquiry, but the nature of his/her activity has changed, now having a wider scope. The resources needed to conduct scientific research now include all those aspects associated with the social and the commercial dimension of scientific research. This new level has been called Level 3 Design Consultant.

Diagram 8.19 illustrates the correspondence between the case studies and the new model of collaboration between designers and scientists.

Even though the immunoassay case study does not match the models exactly (the nature of designer activity sits at an intermediate point between resources and enquiry), the rest of its elements coincide with the model and the level of Design Consultant role is still relevant for this case.

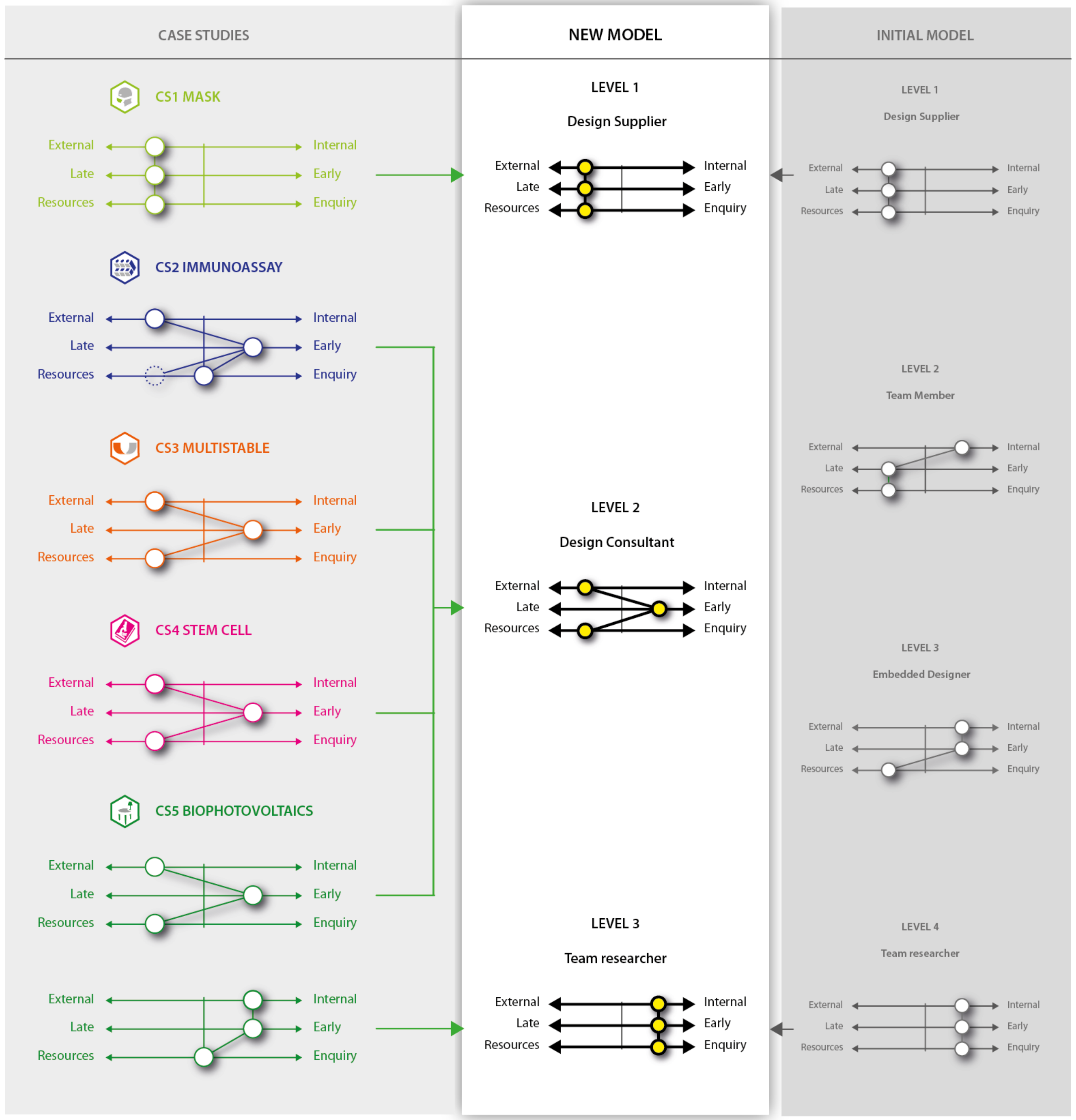

Diagram 8.19 *Case studies and the new (and old) model for collaboration*

8.2.7 Observations on Integration, Project control and Nature of activity

In addition to this new collaboration model, the case studies have demonstrated some unexpected results. It seems that sharing activities is an important aspect of a successful collaboration between designers and scientists. This seems to be the case regardless of the area in which these activities take place, whether in design or in scientific work. It is also apparent that the case studies that produced better collaboration outcome (Immunoassay and Biophotovoltaics) are the ones with more shared activity. For example, in the Immunoassay project, there was intensive shared activity in the design work (6 out of 17 activities), whereas in the Biophotovoltaics project it was in the scientific work (8 out of 24 activities). This contrasted with the Mask project (2 out of 22 in all activities) and with the Multistable project (0 out of 8), as seen in Table 8.1*. However it is difficult to know if sharing contributes to success or if it is a manifestation of a successful collaboration. Either way, the positive value of sharing activities remains.

Also, it is evidently easier for scientists to move towards design activity than for designers to move towards scientific activity. Over all the case studies, scientists carried out 24 design activities (7 individual + 17 shared) whereas designers undertook 16 science activities (7 individual + 9 shared).

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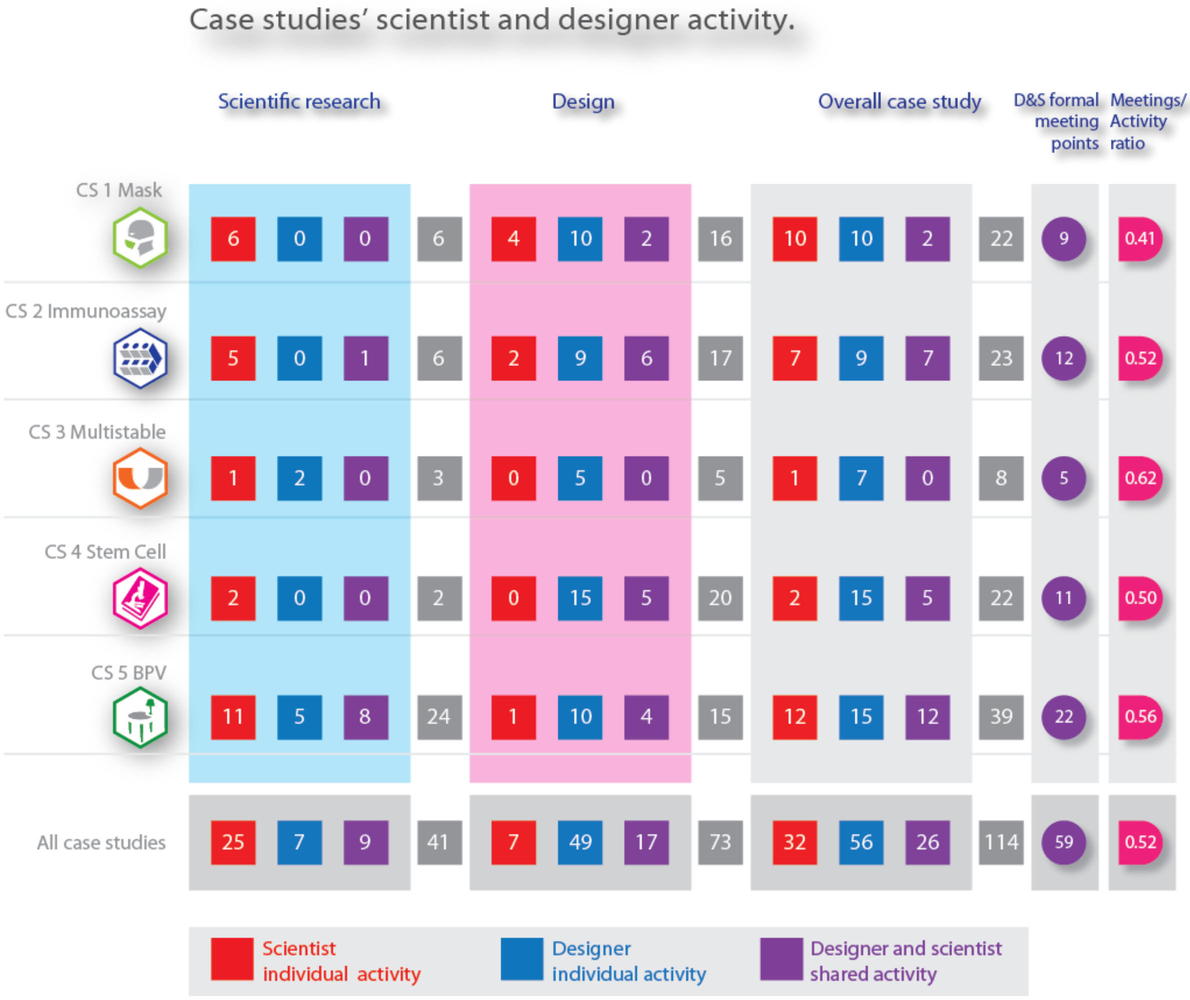
* Numerical comparisons being made should not be interpreted as experimental measures



Case studies’ scientist and designer activity.

	Scientific research				Design				Overall case study				D&S formal meeting points	Meetings/ Activity ratio
CS 1 Mask	6	0	0	6	4	10	2	16	10	10	2	22	9	0.41
CS 2 Immunoassay	5	0	1	6	2	9	6	17	7	9	7	23	12	0.52
CS 3 Multistable	1	2	0	3	0	5	0	5	1	7	0	8	5	0.62
CS 4 Stem Cell	2	0	0	2	0	15	5	20	2	15	5	22	11	0.50
CS 5 BPV	11	5	8	24	1	10	4	15	12	15	12	39	22	0.56
All case studies	25	7	9	41	7	49	17	73	32	56	26	114	59	0.52

🟥 Scientist individual activity
🟦 Designer individual activity
🟪 Designer and scientist shared activity

Table 8.1 *Case studies’ scientist and designer activity*

From the case studies it is noticeable that the level of control (referred to as the designer’s project entry point) does not have a clear role in the success or failure of a collaborative effort. For example, in case studies with a less significant design output, the designers engaged either late (the Mask project) or early (the Stem Cell project) in the project. Again, what seems important is to have both designers and scientists sharing activities.

Finally, it seems that designer activity shifts towards scientific enquiry when the character of the scientific research is applied. However, collaboration in applied research does not automatically lead designers towards contribution on scientific enquiry issues. Instead, it leads them to remain contributing to the area of resources for scientific research. It seems that the main contributing factor that can lead the shift of design activity from resources to enquiry may be intensive interaction over long periods of time, as observed in the Biophotovoltaics case study.

8.3 What roles might designers take in scientific research activity?

In order to examine the role that designers can play in scientific research, this study takes two points of reference. The first is Paton & Dorst's classification of the designer's role in design briefings. As introduced in Chapter 4, Paton & Dorst propose 4 main roles for designers according to their involvement in the definition of the design problem (or design opportunity), the proposal of the primary design concept solution (or design hypothesis), and the designer's point of entry into the design project. These key points have already been individually identified for each case study in the previous section of this chapter. The second point of reference is Chris Rust's list of designer roles in collaboration with scientists identified in Chapter 2. This list defines the roles of designers by describing the tasks they can potentially develop while collaborating with scientists (the role-task).

8.3.1 Designers' roles according to their involvement and point of entry in the project

Following Paton & Dorst's classification, in most cases designers have the role of Experts as shown in Diagram 8.20. In 3 case studies (Immunoassay, Multistable and Biophotovoltaics) the scientists had a partial or complete formulation of the problem, but did not have even a partial conceptual design solution. In contrast, in one of the case studies (the Mask) the designer' role was that of Technician. In that case, the scientists had already identified the problem, formulated a design hypothesis and started the design development before the designers became involved. During the Stem Cell case study the designers' role was that of Collaborator, since the scientists had not previously identified a problem or a design opportunity. It is worth mentioning that in the Biophotovoltaic case study the designers' role changed during the collaboration from Expert to Collaborator. Also, it is noticeable that the role of Facilitator did not occur in any of the case studies.

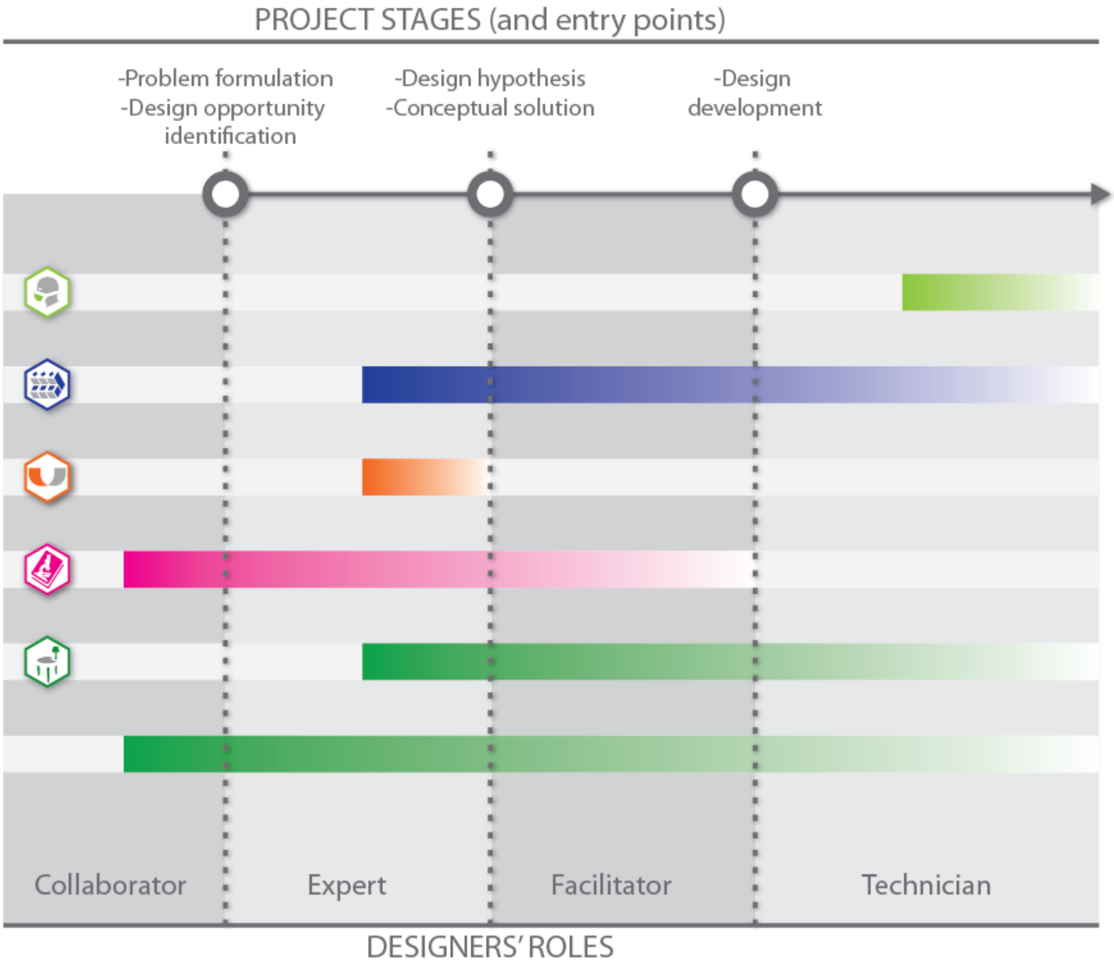
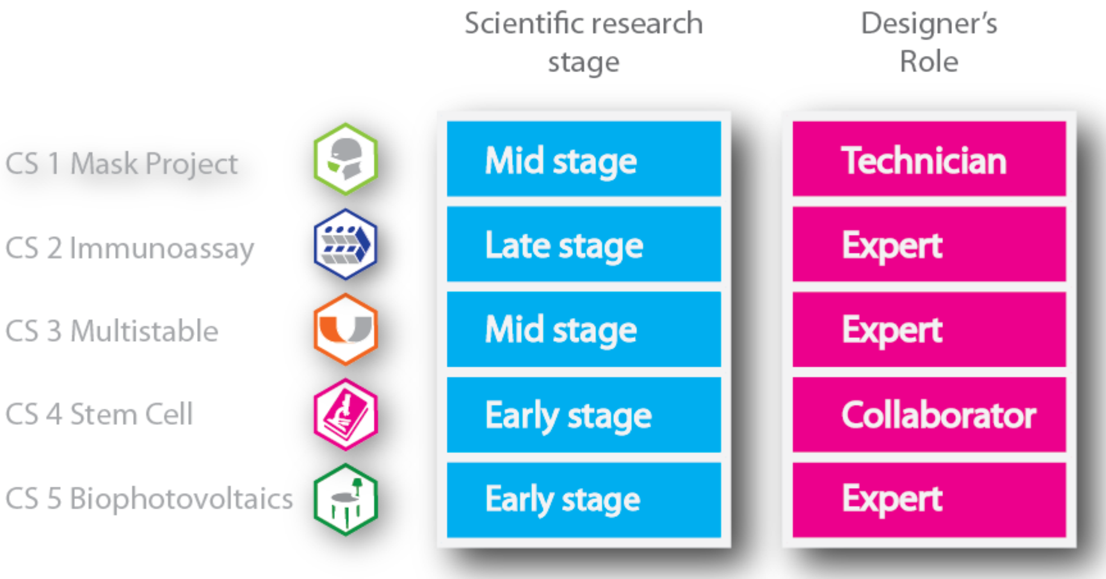


Diagram 8.20 *Designers' roles according to their involvement and point of entry in the project using Paton & Dorst's classification*

It is possible to perceive a relationship between the role of designers and the location of the collaboration in relation to the process of scientific research. For example it could be argued that the designer's role would most probably be that of Technician in the late stages of scientific research, and that of Collaborator in the early stages. This is because in the late stages scientists have probably already identified potential design opportunities and outlined possible conceptual solutions, whereas this is less likely in the early stages. However, as illustrated in Table 8.2, no such relationship or identifiable pattern was observed during the case studies.



	Scientific research stage	Designer's Role
CS 1 Mask Project	Mid stage	Technician
CS 2 Immunoassay	Late stage	Expert
CS 3 Multistable	Mid stage	Expert
CS 4 Stem Cell	Early stage	Collaborator
CS 5 Biophotovoltaics	Early stage	Expert

Table 8.2 *Case studies table relating scientific research stage and designers' roles in collaboration*

8.3.2 Designers' roles according to potential task (Role-task)

Rust lists 5 different roles for designers in collaboration with scientists, defining all of them as tasks expected to be performed. These are:

- Constructing models of representation and simulation
- Designing artefacts for testing and experimentation
- Ideating scenarios
- Finding applications for scientific research outcomes
- Visualising scientific ideas.

However, this list seems not to be enough to reflect all the possible roles that designers played in the study cases undertaken in this research. Although in some of the case studies the designers did not play any of Rust's roles, in all of them additional new roles were identified.

In the Mask case study, the designers had the task of designing artefacts for testing and experimentation. However, their task was also to evolve the scientist's idea of a mask into a product for commercialisation (although this was not completed at the end of the project). From this case study a new task/role arises: *developing scientists' creations into commercial products.*

Similarly, during the Immunoassay case study the designers had the task of designing an artefact for testing and experimentation. In addition, they helped to advance the scientists' concept towards a possible commercial product by creating a design specification based on the scientists' original idea. Since a design specification is not necessarily associated with commercial exploitation (it is possible to create a design specification for a non-commercial product), this is a new separate task/role for designers: *creating design specifications for products derived from scientific research*. Additionally, the designers contributed to the writing of a funding proposal by giving design input, including the design specification and visual records of their immunoassay device design process. This task can represent another role for designers collaborating with scientists: *bringing design input to research (funding) proposals.*

The Multistable case study appears to be the only one in which none of Rust's roles applied. In this case the designers were asked to develop a working prototype of a wearable accessory. The purpose of this prototype was to demonstrate to a possible industrial investor the potential of a technology the scientist was working on. So the task in this case was to design a demonstrator to persuade an investor, who could be described as an object for persuasion. Additionally the designers recognised that the technology was not sufficiently developed to benefit from design input for the purpose of developing a commercial product. From this, two new tasks/roles emerge: *designing elements to attract investment in scientific output* and *diagnosing scientific output readiness for design input.*

In the Stem Cell project, the designers examined research practice in the laboratory looking for problems to solve using design. They looked at aspects of communication between scientists and how this affected their research and working practices. They proposed a system to record and share experiments and protocols. This uncovered a new possible task for designers collaborating with scientists in scientific research: *developing devices to support better scientific working practices.*

The roles of designers in the Biophotovoltaic collaboration matched most of Rust's model. They designed artefacts for testing and experimentation (algae and moss Biophotovoltaic cells), they helped to visualise scientific ideas (by designing posters to communicate research into Biophotovoltaics) and they constructed models of representation/simulation (developing an animation to represent/simulate the energy production of the moss table). They also found applications for scientific findings. However, they went beyond the mere finding of an application using the technology as it stood at that particular moment. By projecting the technology into the future, they created prospective scenarios of use and application, and this can lead to two more potential tasks for designers: *forecasting scientific discovery application* and *developing concepts and scenarios for the future application of scientific research.* Additionally, the designers created the Moss Table, a conceptual object incorporating Biophotovoltaic technology. The purpose of this object was to communicate the potential of Biophotovoltaic technology to a non-scientific audience. This suggests a further role for designers: *creating objects to communicate the potential of scientific research*. Lastly, the designers created visual material to represent and explain the experimental devices the scientists had created before the collaboration started. The scientists used this to present their findings later in academic papers. This suggests yet another task/role for designers: *visualising scientific output and experimental equipment.*

The following table (8.3) summarises the roles that designers can have while collaborating with scientists in scientific research. The roles have been grouped into 5 main clusters according to what aspect of scientific research they focus on: the undertaking of scientific research work, the use of scientific research, the connection of scientific research with design work, the relationship between scientific research work and society/industry, and the visualisation and communication of science. These clusters have been named to describe generic role names that encompass both the known roles and the roles uncovered in this study:

- Scientific research design *supporter*
- Scientific research application *explorer*
- Design and scientific work *integrator*
- Scientific research/society and industry connecting *contributor*
- Science *visualiser* and *communicator*.

Summary of designers’ roles (by task) in scientific research

	CS 1 Mask Project	CS 2 Immunoassay	CS 3 Multistable	CS 4 Stem Cell	CS 5 Biophotovoltaics
Scientific research design ***supporter***					
Constructing models of representation and simulation				●	●
Designing artefacts for testing and experimentation	●	●			●
Creating/specifying devices to support better scientific working practices				●	
Scientific research application ***explorer***					
Finding applications for scientific research outcomes					●
Ideating scenarios					●
Forecast of scientific discovery future application					●
Design and scientific work ***integrator***					
Outlining design specification for products derived from scientific research		●			
Bringing design input in research (funding) proposals		●			
Diagnosing scientific output readiness for design input			●		
Scientific research/society and industry connecting ***contributor***					
Developing scientist’s creations into commercial products	●	●	●		
Designing elements to attract attention/investment in scientific output			●		
Science ***visualiser*** and ***communicator***					
Visualisation of scientific output and experimental equipment					●
Visualising scientific ideas					●
Creating objects to communicate the potential of a particular scientific research					●

BLUE: Generic role *DARK GREY: New role from case studies* *LIGHT GREY: Known role*

Table 8.3 *Summary of designers’ roles (by task) in scientific research*

8.4 What contributions might designers make to scientific research activity?

Contributions to scientific research activity were identified in Chapter 2 of this study. This section identifies and explains the contribution that designers have made in all case studies. It also compares them with the ones identified in existing literature, and clusters them under several distinct categories that represent those aspects of scientific research that has been/can be affected by design intervention.

8.4.1 Contributions to the Mask case study

The designers' contribution to the mask project was centred on the design development of the mask as an experimental device and as potential commercial product. By generating an initial design specification for the mask, the designers made the scientist aware of several design aspects such as comfort or visual appearance, making the gap between the scientist's original concept and a usable/marketable concept explicit for him.

The designers developed several iterations of working mask prototypes, with variations of sealing principles, materials and element configurations. This made it possible for the scientist to start gathering data for his research into oxygen therapy. It also facilitated the testing and comparison of various sealing principles, thus allowing the scientist to challenge his previous ideas on the subject, and to build a better understanding of these principles.

In the Mask case study the designers' contribution coincides with several of the possible contributions listed in this study in Chapter 2, as illustrated in Table 8.4 at the end of this section.

However, it is apparent that the contribution derived from the design specification of the mask did not match any of those included in Chapter 2. The contribution '*improved scientist's understanding of possible gaps between their research-inspired product ideas and a usable/commercial product'* has therefore been added to the new list in table 8.4 Also added to this list is the overarching contribution to this project: *support the development of scientific ideas towards future commercial application.*

8.4.2 Contributions to the Immunoassay case study

The designers' contribution to the Immunoassay project was centred on the development of a device for conducting immunoassays utilising MCF as its main element. They aimed to develop a working prototype of the device for the later production of a testing batch, and the eventual development of a commercial version.

At the beginning of the collaboration the designers made visualisations of the immunoassay process as an instrument to verify their understanding of it. Although this was not intended as a contribution, the scientists adopted this design communication style in public presentations about their work. Thus the designers introduced useful and relevant communication skills to the scientists.

The designers made a series of sketch models and functional prototypes of various alternative immunoassay devices. This made it possible for the scientists to conduct experiments to evaluate the best devices and chose a preferred alternative for further development. While doing this, the scientists increased their understanding of the working principles of MCF for immunoassay tests and were able to compare their device with competing technologies. Apart from helping the scientists to take their initial idea closer to a real product, the designers helped them to understand the functional and commercial potential of their ideas.

One of the purposes of the scientists' initial concept was to make the immunoassay test quicker by improving the device. However the designers' systemic approach of examining the immunoassay process within the context of the laboratory helped them to design a device that was quicker, easier and safer to use. By doing this, the designers contributed to improving laboratory working practices.

At the end of the collaboration the designers developed a specification of basic principles for a suitable design of an immunoassay device using MCF. With this the scientists were able to engage additional design and engineering support to develop the device for laboratory testing. In this way, the designers gave the scientists information to support an informed dialogue with possible new collaborators.

The design input was also utilised by the scientists to apply for and secure additional research funding to continue with the development of their idea. The funding application included images of the models and prototypes, and test results.

Again, these contributions correspond to several known contributions previously identified in Chapter 2. However as explained before, some new contributions were uncovered from the immunoassay case study. These are:

- *Helping scientists to understand the functional and commercial potential of research output*
- *Supporting scientists in dialogue with other external design/engineering collaborators.*
- *Supporting scientists in research funding and sponsorship applications.*
- *Improving research laboratory working practices.*

8.4.3 Contributions to the Multistable case study

The designers' contribution to the Multistable project was centred on the development of a small device made of a material formed by a multistable process. Since this device was intended to be smaller than any previous devices made using the multistable forming process, the design intervention also focused on finding ways to scale down the technology. The aim was to use the small device as a demonstrator of multistable technology to take to possible industrial investors.

By learning and practicing the multistable forming process the designers gained practical knowledge of it. From this they realised that in order to scale down the technology, further basic research on various aspects of the process was needed before they would be able to make a useful design intervention. They specified these aspects for the scientist and in this way they made a contribution absent from Rust's list: *helping the scientist to understand the current technology readiness level for design intervention towards commercialisation.*

Before the collaboration ended, the designers proposed to the scientist an experimental technique based on laser engraving that could potentially provide an empirical method of identifying parameters required for conferring multistable properties upon small material samples. In the long run this could lead to the development of the small device the scientist was looking for. In this way, the designers contributed to the research in a new form by identifying possible new areas for scientific enquiry. The scientist saw the potential of the idea but explained that its development would require resources he did not have available. By the time this was discussed the scientist had already moved on onto a new project, so the collaboration reached its end.

8.4.4 Contributions to the Stem Cell case study

The contribution of designers in the Stem Cell project focused on improving communication between researchers at the lab. The designers developed a concept for an interactive tool that would enable scientists to record protocols and experiments, and to pass them on to other colleagues.

Through the development of this concept, the scientists reflected on their own communication working practices and contributed to the development of the tool for a possible solution. In this way designers made a new form of contribution by *prompting scientists' self-reflective attitude regarding their working practices*.

During the design process, the tool became more sophisticated, including a research timeline and a research mapping function amongst others. At that point the designers realised that their concept was becoming very similar to an electronic laboratory book. After some market research they realised that some existing electronic laboratory books already had most of the functions of their design and would therefore be a suitable alternative to embarking on the development of a new tool. From this, they produced a recommendation of the best available e-lab books for the scientists. This shows a new contribution by designers to scientific research: *creating/specifying means to support better scientific working practices.*

8.4.5 Contributions to the Biophotovoltaic (BPV) case study

The designers' contribution to the Biophotovoltaics project was the development of various elements to communicate and disseminate Biophotovoltaic technology amongst non-scientific audiences. The first part of the project was centred on the design of graphic material and on the design and construction of a demonstrator for a science exhibition. During the second part, design efforts were geared towards the design and manufacturing of a conceptual object (the moss table) and its presentation at design events.

At the beginning of the collaboration the designers made schematics and three-dimensional computer visualisations of the scientists' BPV device as an instrument to verify their understanding of it. As in the Immunoassay project, this was not intended as a contribution, but the designers' communication style influenced the scientists and they adopted it for their research communication. This brought new skills to the scientists, and highlights a new type of designer contribution to scientific research activity: *bringing visualisation skills to the* *communication and understanding of experiments, experimental equipment and scientific research output.*

As part of the development of the graphic material, the designers generated concepts and scenarios for future applications of the BPV technology. These took the form of products and systems, and were intended to be easy for non-scientists to understand. During their exhibition at the science fair, the concept images attracted the attention of a wide variety of observers and helped the scientists to explain their research and the BPV technology. The concepts for BPV future applications had also an impact on the scientists' research. They led the scientists to identify and address new scientific questions associated with each of the concepts.

Also, the designers developed demonstrators that made the technology easy to understand by up-scaling its components, and shaping it in a way that these components were easily identifiable and related to their function. Furthermore, the device's curvaceous and well-proportioned shape made it friendly and attractive to the observer. In this manner, designers contributed by *facilitating the communication of the potential of scientific research projects.*

Due to its shape and size, the device produced water as a by-product from photosynthetic activity in sufficient quantities to be collected and tested for salinity. Although the demonstrator had not been designed for this purpose, it helped the scientists to prove a hypothesis that the device was capable of desalinating water (which they had been unable to confirm with their existing devices). This suggests that a different approach by designers can open up new contexts for scientific enquiry and endorses serendipity as a route towards scientific discovery. This can be identified as a new form of contribution.

During the second part of the project, designers and scientists collaborated on the development of one of the concepts proposed by the designers. While considering the scientific feasibility of the BPV table concept, the scientist concluded that algae (the organism that has been principally used for BPV research) was too fragile to be used for this application, and that moss was a more suitable organism due to its resilience and low demand of light. This led the scientists to initiate a new line of enquiry into moss as part of their BPV research. In this way the designers were able to steer the research in a new direction.

The designers took responsibility for the formal development and manufacturing of the concept (named the moss table). Simultaneously, the designers and the scientists engaged in the design and development of the 'moss pots' - small containers wired to the table that would host the moss and act as biophotovoltaic batteries. During the design development of the moss pots, designers and scientists engaged in an iterative process of testing and trial, experimenting with different components configurations. This process served the scientists to generate useful BPV scientific data and to better understand BPV phenomena, accelerating their understanding on their research subject. This reveals a new potential contribution by designers to scientific research, by focusing scientific efforts on resolving science-related design project issues: *providing a new context (design process) for the practice of scientific research.*

As the moss pots were perfected and built, the moss table was also successfully built. It was then exhibited in two major international design exhibitions. During the exhibitions, the moss table attracted the attention of people of all ages and backgrounds and was fundamental in explaining BPV technology to people with no scientific background. It also attracted the attention of journalists that helped to disseminate BPV research through online and printed magazines and TV. In this manner designers contributed by creating objects to help disseminate scientific research.

8.4.6 Summarising Contributions

The following table (8.4) summarises the contributions that designers can make to scientific research activity. The table includes contributions already identified in previous studies (as illustrated in Chapter 2) and newly recognised contributions. In the table, similar contributions have been clustered into seven distinct categories that represent those aspects of scientific research that has been/can be affected by design intervention. These categories are:

- Commercialisation of scientific research
- Research undertaking and research work practices
- Context for scientific research
- Thinking in scientific research
- Scientific research enquiry direction
- Connecting scientific researchers
- Competencies for scientific research.

One of the contributions from previous studies did not fit in any of these clusters, so in the table it appears as a single cluster:

- Socialising and humanising technologies.

The table also highlights which contributions have affected the dimensions of scientific research. This does not relate solely to the case studies but to collaboration in general, and shows that designers can contribute to scientific research in all its dimensions. The table indicates that in the case studies there were more contributions that impact the rational dimension of scientific research than the other two dimensions. Also, it illustrates that designer contributions have had a major effect in two main areas: ways of thinking in scientific research and competencies for scientific research. Additionally, the case study contributions reveal an area not previously identified: the commercialisation of scientific research.

Designer contribution to scientific research

BLUE: Affected aspects of scientific research
DARK GREY: New contribution from case studies
LIGHT GREY: Known contribution

	CS 1 Mask Project	CS 2 Immunoassay	CS 3 Multistable	CS 4 Stem Cell	CS 5 Biophotovoltaics	Social Dimension	Rational Dimension	Commercial Dimension
Commercialisation of scientific research								
Improving scientists' understanding of possible gaps between their research inspired product ideas and a usable/commercial product	●	●	●					●
Helping scientists to understand the technology level of readiness for design intervention towards commercialisation	●	●	●					●
Supporting the development of scientific ideas towards future commercial application	●	●	●					●
Supporting scientists to understand the functional and commercial potential of research output	●	●	●					●
Research undertaking and research work practices								
Improving research lab working practices		●		●			●	
Creating/specifying means to support better scientific working practices		●		●			●	
Facilitating the advancement of scientific research, by providing means of experimentation and reflection	●	●			●		●	
Engaging in actual invention	●	●			●		●	
Supporting scientists in research funding and sponsorship applications		●				●		●
Context for scientific research								
Repositioning of scientific findings into a new context					●		●	
Opening up new contexts for scientific enquiry and favours serendipity as a way for scientific discovery					●		●	
Providing a new context (design process) for the practice of scientific research	●	●			●		●	
Thinking in scientific research								
Bringing divergent thinking (Contrasting convergent)	●	●			●		●	
Providing lateral thinking about technology and science	●				●		●	
Prompting scientists' self-reflective attitude in regards to their working practices		●		●		●	●	
Challenging dominant structures in scientific research					●	●	●	●
Unlocking "tacit" knowledge		●		●			●	
Scientific research enquiry direction								
Identifying possible new areas for scientific enquiry			●		●		●	
Challenging scientists' perceptions and encouraging the pursuit of new research directions.	●		●				●	
Connecting scientific researchers								
Connecting scientists with the non scientist, and helping to disseminate scientific knowledge amongst the general population					●	●		
Supporting scientists in dialogue with other external design/engineering collaborators		●				●	●	●
Competences for scientific research								
Bringing disciplinary knowledge	●	●			●	●	●	●
Bringing communication, design and project management skills		●		●	●	●	●	●
Bringing visualisation skills for the communication and understanding of experiments, experimental equipment and scientific research output		●		●	●	●	●	●
Socialising and humanising technologies						●		●

***Table 8.4** Summary of designer contribution to scientific research*

8.5 What are the barriers to and enablers of collaboration?

Barriers to collaboration have been previously identified in this study. While Chapter 2 outlined a list of specific barriers to collaboration between designers and scientists, in Chapter 6 a more generic list drawn from literature on interdisciplinarity was presented. In the same way, enablers of collaboration have been outlined, but they have been identified only from literature on interdisciplinary studies.

This section identifies and explains the barriers and enablers encountered in all of the case studies. It also compares them with those identified in Chapters 1 and 6, and clusters them into several distinct categories that represent those aspects of collaboration to which they relate. It also identifies which barriers and enablers seem to be specific to collaboration between designers and scientists.

8.5.1 Barriers and enablers in the Mask case study

Some barriers to collaboration in the Mask case study related to the low levels of integration between the designers and the scientist. For example, the designers and the scientist had very limited opportunities for contact and shared activities. Most of their interactions happened during presentation meetings. Unlike the other case studies the scientist did not participate in the initial brainstorm session at the start of the Mask project. This denied the scientist and the designers access to valuable insights into each other's style of work and way of thinking.

Restrictions placed on the designers preventing them from participating in the testing of their ideas on patients (due to issues of ethical approval) had a detrimental impact on the collaboration. For instance, the designers were not able to evaluate their design proposals based on their own observations and design criteria, but had to rely on the quantitative results collected by the scientist, and on his own interpretation of them. This limited the designers' ability to fully continue developing their ideas based on their own informed understanding of the problem.

Another barrier to collaboration related to the dependence of the research project on an individual researcher rather than on a research group. As the mask project reached a critical moment and was getting closer to a final resolution, the scientist left the university to work somewhere else. For this reason the project did not continue. If this research had been conducted by a team of scientists rather than by an individual, it would have been less vulnerable to the researchers' departure.

A further noticeable barrier to collaboration related to the working style of the designers and the scientist. The designers seemed to prefer developing several competing concepts at the beginning of the design process before ultimately committing to a final design. When the initial testing of this final idea failed, they proceeded to modify it whilst trying to keep the overall concept intact. They were expecting to have a perfected and working version of it after various iterations of testing and refinement. By contrast, the scientist seemed to work in a linear sequence of individual ideas. He would develop an idea up to a stage to be tested and then, if the test showed that the idea did not match all requirements, he would discard it and move onto a new concept.

An additional barrier was the preconceptions that the scientist had about the designers' capabilities. At the start of the project the scientist said that he was looking for design input to help him because he did not know about materials and he was not able with his hands. In an interview after the project he demonstrated that his view of designers as material experts and craftspeople had not changed.

From the previous point derives a final barrier, which is the designers' failure to thoroughly investigate previous experiences the scientist may have had with designers, and to learn what might be their expectations in relation to design capabilities. Furthermore, the designers failed to emphasise their competencies at the beginning of the collaboration.

One last barrier was encountered when the scientist approached the research team with his own solution to the problem of sealing to the face. Even though his theory as to why his solution provided a good seal was eventually proved incorrect, it was very difficult for the designers to persuade him to consider alternative options.

Several aspects acted as enablers in the Mask project. For example, the active participation and engagement of both designers and the scientist during the project played an important role keeping the collaboration running. The scientist conducted thorough testing of the prototypes made by the designers and generated data for their evaluation.

Another factor that enabled collaboration was the allocation of resources for design development costs. This was important since the making of prototypes was expensive, but deemed to be the only way of testing the designers' ideas.

A further enabler was related to the designers' ample range of design skills. The development of this project required the use of different types of computer 3D modelling software and physical prototyping skills working with a variety of materials. This combination of skills is not a default characteristic in every design team, and it was fortunate they were present in this particular team.

The involvement of the UTTO officers in the collaboration was helpful and they actively contributed in meetings, offering helpful feedback on the design proposals and helping sometimes to advise the group on various issues such as IP and commercialisation routes. They also helped the group to take decisions at critical milestones.

8.5.2 Barriers and enablers in the Immunoassay case study

Very few barriers were encountered in the Immunoassay project. However some issues regarding communication acted as a barrier in this project. For example, the designers' understanding of some important aspects and features of the projects was hindered to start with by the scientists' use of specialised vocabulary and acronyms. This caused the design team to miss important pieces of information that affected the project's development at the beginning. (On one occasion the designers spent time developing a prototype that was not needed).

Due to the small scale of the objects the designers were developing, they encountered some difficulty in making testable sketch models. Their existing model-making skills and the tools and equipment they had available were not suited to such small-scale work. Consequently they had to resort to external suppliers to create models for them using rapid prototyping equipment. This meant that the designers had to create 3D computer models of their concepts, and then embark on a process of quotation-approval-order every time they wanted a new sketch model built. This slowed down the project and increased its cost.

The communication problem experienced by the team at the beginning of the project was eased by the scientists' efforts to modify their normal way of speaking about their research. They actively avoided as much technical terminology as possible while talking to the designers, and they took the time to further explain what they meant when they felt the designers did not understand them. On their part, the designers made an effort to learn more about the science by reading papers and conducting Internet research.

An important enabler of collaboration was the visualisations the designers created at the beginning of the project. These were made with the purpose of relating the immunoassay process and its technical terms to graphic elements, and to confirm that their understanding of the process was accurate. These graphics became a valuable tool for the designers as a reference while designing, and were also of use to the scientists. The scientists explained after the collaboration that they had drawn inspiration from them to present their findings in new ways in their scientific publications.

Another enabler was the high level of engagement of the scientists with the project and their readiness to spend time with the designers. This brought an effective dynamism to the collaboration, and helped to transform the feedback meetings into intense brainstorming sessions. This helped the designers to address the project needs whilst taking into account the scientists' views. Also, thanks to these sessions, the team adopted a practice of making decisions by consensus.

Another enabler relates to the scientists' attitude towards designers and their acknowledgement of their abilities. Even though the scientists contributed with design ideas, they never tried to impose them, and often explicitly stated that they trusted the designers and that their ideas were only suggestions. This made the designers feel confident and motivated, and made them more receptive to the scientists' ideas. Connected to this, another enabler was that the scope of the project was clearly defined from the outset. From the beginning of the project, it was agreed that the designers' contribution would end with the construction of a working prototype. After that, the scientists would engage with an external design consultant to prepare the concept for the manufacture of a small batch of products.

Another enabler was the thoroughness that the scientists showed whilst testing and evaluating the designers' proposals. When one of the designers presented an idea that strongly challenged the main principle of the scientists' concept, they produced an extensive report to counter it. The report evaluated the designer's idea and demonstrated the validity of their original concept.

As in the Mask case study, the allocation of funds for outsourcing model making became an important enabler of the project, since rapidly prototyped models were necessary to prove the validity of the designs.

A final enabler of this project was the good personal rapport established between the designers and the scientists. On a few occasions they engaged in mixed social/working activities. During those events, they had useful discussions and made important decisions about the project.

8.5.3 Barriers and enablers in the Multistable case study

During the Multistable project a number of important barriers were encountered, which eventually led to the termination of the collaboration. First, the designers failed to explain their competencies early on in the project. This was problematic since the scientist's expectations did not closely match the designers' capabilities. He was rightly expecting that the designers would develop a wearable accessory using a sample of multistable material. However, he also expected that the designers would design new manufacturing equipment and adapt the forming process to the fabrication of smaller samples of multistable material. These last tasks were more suited to a mechanical or industrial engineer.

Also, the designers did not have access to one of the key scientists who had developed the practical aspects of the multistable forming process, since he had left the laboratory to work somewhere else just before the collaboration started. The scientist participating in this case study had developed a theoretical explanation of the forming process, but his knowledge about specific practical aspects of the process was limited. This hindered the designers' ability to use the existing multistable forming process to build sketch models and prototypes as a starting point for the development of their concepts and ideas.

Additionally, the scientist's requirement for the development of a new multistable product (the wearable accessory) was not opportune since the process required to make it was not yet fully developed and standardised. Therefore the immediate need of the project seemed to be to further develop the multistable forming process. Since this was outside the scope of the designers' capabilities, product design input became irrelevant and the collaboration was eventually suspended.

A further barrier that emerged during this collaboration relates to the collaborators' motivation. Although the project was aiming for the commercialisation of multistable technology, as soon as it became clear that the technology would require more development, the scientist lost interest and chose to focus his efforts on projects more oriented towards basic research. This loss of motivation was also the result of the scientist knowing how difficult it would be to obtain additional funding to continue developing the technology.

Connected to this barrier was the adverse impact that the scientist's other duties had on the collaboration. Since he was in a senior position, he was sometimes too busy with other activities and commitments to make his required contribution to the project.

Only two enablers were identified in this case study. The first was the participation of an UTTO officer, who followed the project from the beginning and promoted team meetings during which he took an active role, providing information from prospective industrialists interested in multistable technology and offering market insights on the potential of the technology.

The second enabler was the provision the scientist made for the designers, so they had access to the space, equipment and materials necessary to experiment with the multistable manufacturing process.

8.5.4 Barriers and enablers in the Stem Cell case study

Stem cell research is a complex theme, which draws on biology, human physiology, and biochemistry amongst other sciences. Its abstract nature and distance from the designers' normal experiences became a barrier to collaboration. During the whole project the designers spent a great deal of time and effort on gaining just a basic understanding on stem cell research. As a consequence of this, they eventually turned their attention to issues closer to their experience and expertise. Focusing on the working practices of the scientists, they developed a project to improve communication in the lab. Had the scientific research subject been more accessible, the designers would probably have attempted to contribute to the rational dimension of the scientific research.

That barrier might be connected to another one related to time limitations. It would be reasonable to expect, after a certain amount of time spent studying and interacting with the scientists, that the designers might have gained sufficient knowledge of stem cell research to attempt to make a meaningful contribution. However, the restricted length of the project prevented this from happening. Furthermore, since the collaboration was not the first priority for the scientists involved, the designers felt that they should not ask for too much time from them, to avoid becoming a burden. This meant that there was less contact and therefore fewer opportunities to learn from the scientists and their research.

Another barrier during the Stem Cell project was associated with the collaborators' motivations. For example, even though the scientists were interested in the collaboration, they did not know what to expect from it and their participation was mainly driven by curiosity (and good will). They wanted to know what product design could do for their research. As a consequence of this the scientists took a passive role in the collaboration and left the responsibility of leading the project to the designers. Although this offered advantages to the design team, for example being able to choose the design issue they found more useful and interesting, it also brought some disadvantages. For example, they missed the scientists' insight into design opportunities that was present in other case studies. Additionally, since there was no real pressure from the scientists to see the advancement of the project, the sense of urgency present in other case studies was absent, and this contributed to an unnecessary extension of the project duration by the designers.

An important enabler of the Stem Cell project was the good will and open attitude of the scientists involved. As well as “opening the gates” for the designers so they had access to the laboratory, they spent a considerable amount of time answering questions and demonstrating some of the processes and practices of daily routine in the lab. They also allowed the designers to participate as observers in one of their weekly laboratory staff meetings. From this specific meeting, the designers were able to identify the issue they eventually decided to address during the collaboration. The scientists also engaged actively with designers during project meetings and provided valuable insights for the project.

As in other case studies, the visualisations produced by the designers became important instruments in supporting communication between designers and scientists. They not only helped the designers to confirm that they had understood the scientific concepts, they also enabled them to unpick tacit information from the scientists.

A further enabler was the designers’ computer web design skills. These skills (not typically possessed by product designers) made it possible for them to prototype the concepts so that they could be discussed with the scientists.

8.5.5 Barriers and enablers in the Biophotovoltaics case study

There were no recognisable barriers to collaboration in the Biophotovoltaics project. Aspects that had a negative effect during other case studies worked to the team's advantage during the Biophotovoltaic project, helping it to become a successful collaboration; these included the different working styles of scientist and designers and the scientist' ignorance about the potential contribution of designers in scientific research.

Perhaps the only aspect that adversely affected collaboration happened during the second part of the project. The designers and the scientist struggled to secure the necessary funds to exhibit the moss table at design fairs on time. This happened because the resources were coming from different funding sources and the responsibility of securing them was in the hands of several different senior scientists. Even though eventually the funds were made available on time, it could have happened otherwise and had a negative impact on the project and the collaboration.

The early involvement of the scientist in the design process, by participating in the initial project brainstorming session alongside the designers, became one of the first collaboration enablers. From this the scientist become familiar with the designers' way of thinking and working, and helped to smooth the potential communication problems that could have arisen between them. Later on in the project, the designers had the opportunity to help the scientist in his laboratory with some of his data collection chores. This had similar effect and made the designers understand further the scientist's ways of working and thinking.

Even though designers and scientist crossed over and participated in both design and science activities, there was always a clear mutual sense of the boundaries between design and science activity, and the team frequently made this explicit in project planning meetings. At most points during the project, the team knew what to expect in terms of science and design project development, and how development within each of these aspects was interconnected. For example, until they knew the maximum achievable electricity production per square metre of the moss (a scientific task), the designers were not able to finish designing the final layout of the moss pots in the table (a design task).

The efforts that the design team made to understand the Biophotovoltaic technology became also an enabler of collaboration. At the first meeting the scientist who eventually worked closely with the designers was not impressed by their questions. He thought that they were far too basic, and found it difficult to imagine how these designers would contribute to the project. However as the time pass the designers read about the technology and the science, and came up with other more complex questions that demonstrated to the scientists that they were learning quickly, and rightly picking the most relevant information from the project. This helped to build trust in the team. As in other case studies, the designers' initial visualisations of the technology served as a collaboration enabler. They were employed as a communication device, but the scientist also perceived them as a useful tool that he could adopt for his work.

Both designers and scientist were fully engaged with the project and had additional motivations apart from their interest in the subject. For example the designers knew that this could be potentially one of the most important case studies of their research, while the scientist integrated the project into his doctoral thesis. These extra motivations became a project enabler.

Another important enabler was the frequency of contact between the designers and the scientist. There was a constant flow of communication by email and telephone and face-to-face conversations, which helped to keep the project workflow running. This frequency developed with the project, becoming intense at some critical points. Even though the designers and the scientist were each working in different locations, they were close enough to organise last-minute meetings, or to leave or collect materials, samples, etc., in person instead of using courier services.

Lastly, as in other case studies, empathy and personal affinity between designers and scientists seems to play an important role in the smooth running of the collaboration. A humorous rapport also seems to be important, especially when designers and scientists spend long hours working together.

8.5.6 Summary of Barriers

The following tables (8.5 and 8.6) summarise the potential barriers to collaboration between designers and scientists in the context of scientific research. The tables includes barriers already identified in previous studies looking specifically at designers collaborating with scientists as illustrated in Chapter 2, and barriers identified from interdisciplinary studies as presented in Chapter 6. The tables also integrate the barriers identified from the case studies. All of the barriers have been clustered into eight distinct categories that represent the aspects of collaboration from which they originated. These categories originate in the barrier summary tables in Chapters 1 and 6. They are:

- Context
- Group dynamics
- Collaboration settings
- Personal characteristics and attitudes
- Disciplinary background and competencies
- Communication (vocabulary and tools)

- Approach and methods
- Focus and epistemological stance.

The tables show how the case studies point to three main aspects of collaboration that are a great source of barriers. First, they highlight collaboration settings, in particular those relating to time management: deadlines and provision of time to allow the designers to develop their scientific knowledge as well as enough contact/interaction time with the scientists. This aspect also includes potential problems related to the scientists' level of readiness for design intervention. Secondly, they point to personal characteristics and attitudes, emphasising potentially false or unrealistic expectations about design and designers. Lastly, there is the communication aspect that highlights the designers' failure to communicate their capabilities.

It is also clear that the case studies have made possible the identification of barriers not seen in previous studies. In addition, it is noticeable that almost none of the barriers encountered in the case studies coincide with the barriers specified in the previous literature about designers and scientists collaborating. By contrast, they coincide with some of the barriers identified in interdisciplinary literature. The lack of coincidence might be related to the way in which the barriers were investigated (by case studies in this research compared with obtaining information though secondary sources in previous literature). However, it may also be the case that a great variety of collaboration instances can generate a great variety of barriers, and that more studies need to be conducted in order to identify a more definite spectrum of barriers.

Barriers to collaboration summary (1/2)

BLUE: Barriers clusters
DARK GREY: New barriers from case studies
LIGHT GREY: Known barriers

				CS 1 Mask Project	CS 2 Immunoassay	CS 3 Multistable	CS 4 Stem Cell	CS 5 Biophotovoltaics
	Context							
1	Time/access to equipment constrains, rigid budget and admin categ. or restrictive legal mandates/policies, bureaucracy, ethical approval		🟩	◉	◉			◉
2	Lack of incentives and inadequate reward systems	🟥	🟩					
3	"Excessive organizational baggage": Fixed perception of others, status in the organization, preconceived ideas of roles, etc.		🟩					
4	Undersized social network (Opposes to Klein's "Excessive organizational background ")		🟩					
5	Not getting access: "Competition for Peoples time and attention ". Key people absent		🟩			◉		
	Group dynamics							
6	Strong groups can be undermined by: Unstable membership and unwillingness to take risks, dependance on key researchers		🟩	◉				
7	Conflict may appear over technical issues (def. of problems, research meth, etc) or interpersonal issues (leadership style,etc)		🟩					
8	Tokenism: Disciplines represented in teams but not included in decision making processes		🟩					
9	Hierarchical structures silencing "lower status" disciplines		🟩					
10	Disciplinary policing/disciplinary superiority bullying		🟩					
11	Status differences		🟩					
12	Disciplinary defaulting can happen		🟩					
13	Imbalance of time availability for dedication to the project						◉	
	Collaboration settings							
14	Absence of a reporting structure	🟥						
15	Lack of definition of communication channels	🟥						
16	Physical separation between collaborators	🟥	🟩					
17	Late entry point into the project	🟥						
18	Lack of situational awareness: Lack of orientation of newcomers in organizations/research groups		🟩					
19	Lack of mutual advantage: Unfair distribution of benefits amongst collaborators		🟩					
20	Interferences with research from other duties the researcher may have		🟩			◉		
21	Un-readiness of science for application					◉	◉	
22	No sense of urgency or precise deadlines						◉	
23	Lack of time to develop enough knowledge of the science			◉			◉	
24	Limited contact/interaction opportunities			◉				

🟥 *Barriers to collaboration between designers & scientists as identified in chapter 1*
🟩 *Barriers to interdisciplinary collaboration as identified in chapter 5*
◉ *Barriers found in case studies*

***Table 8.5** Summary of barriers to collaboration between designers and scientists (1/2)*

Barriers to collaboration summary (2/2)

BLUE: Barriers clusters
DARK GREY: New barriers from case studies
LIGHT GREY: Known barriers

		Designers & Scientists ch1	Interdisciplinary ch5	CS 1 Mask Project	CS 2 Immunoassay	CS 3 Multistable	CS 4 Stem Cell	CS 5 Biophotovoltaics
	Personal characteristics and attitudes							
25	A poor "designer self-image" leading him/her to be relegated to a "subsidiary role"	🟥						
26	"Possible Collaborators" may not recognize designers' contributions	🟥						
27	Lack of disciplinary recognition	🟥						
28	Social and psychological impediments: Resistance to innovation, mistrust, insecurity, marginality		🟩					
29	Limited transaction memory: Unawareness of other people's knowledge		🟩	◉		◉		
30	Social overload: Senior researchers reluctant to collaborate		🟩					
31	Fixed and narrow preconceptions about design and designers			◉				
32	Unrealistic or imprecise expectations about design and designers			◉		◉		
33	Passive role of scientist						◉	
34	Lack of motivation					◉		
35	Fixation on own ideas/lack of flexibility			◉				
	Disciplinary and interdisciplinary background and competences							
36	Participants may lack: Integrative skills, system thinking, and familiarity with interdisciplinarity		🟩					
37	Different disciplinary language	🟥						
38	Inexperience of designers (For example working on a very small scale)				◉			
39	Science abstruseness and distance from designers' normal experiences and knowledge						◉	
	Communication (vocabulary and tools)							
40	Little knowledge of terminology		🟩		◉			
41	Different ways and styles of communication e.g visual vs. written	🟥						
42	Communication difficulties the participants had due to the lack of "any shared formal language"	🟥						
43	Designers lack of communication about own disciplinary competences			◉		◉		
	Approach and methods							
44	Different approach to problem solving	🟥		◉				
45	Different methodological approach (intuitive/subjective vs. Scientific rational and objective)	🟥		◉				
	Focus and epistemological estance							
46	Project focus divergence (what is important)	🟥						
47	Disciplinary assumptions (status quo vs change) (real insight vs on their behalf)	🟥						

🟥 *Barriers to collaboration between designers & scientists as identified in chapter 1*
🟩 *Barriers to interdisciplinary collaboration as identified in chapter 5*
◉ *Barriers found in case studies*

***Table 8.6** Summary of barriers to collaboration between designers and scientists (2/2)*

8.5.7 Summary of Enablers

The next tables (8.7 and 8.8) summarise the potential enablers of collaboration between designers and scientists in the context of scientific research. The tables include enablers identified from interdisciplinary studies as presented in Chapter 6, and integrate the enablers found from the case studies. Unlike the barriers tables, these tables do not include enablers from previous studies looking specifically at designers collaborating with scientists. This is because no reference to enablers was found in that literature.

The enablers have been clustered under six different headings that represent aspects of collaboration from which they originated. Most of these categories originated in the barrier summary tables in Chapter 2.

- Collaboration process
- Collaboration settings
- Resources
- Communication
- Attitude and behaviours
- Approach and method.

The summary tables reveal several points. Firstly, the case studies have helped to identify enablers not identified in previous literature about collaboration. These enablers have been grouped as either *Collaboration process* or *Resources*. While the first cluster refers to enablers that emerge while the collaboration is taking place, the second alludes to enablers related to the availability and sufficiency of resources to carry out the collaboration. Secondly, the enablers found in the case studies related to communication seem to be exclusive to collaboration between designers and scientists and not generic to all kinds of interdisciplinary collaboration. This indicates that good communication might be one of the fundamental aspects to support successful collaboration between designers and scientists. Finally, while some generic interdisciplinary enablers were not relevant to the case studies, some of the case study enablers were not found in the generic interdisciplinary enablers. This suggests that collaboration between designers and scientists is different from collaborations between other disciplines, and that there is potential for cross-referencing and reciprocal learning between all such collaborations.

Enablers of Collaboration Summary (1/2)

BLUE: Enablers clusters
DARK GREY: New enablers from case studies
LIGHT GREY: Known enablers

			CS 1 Mask Project	CS 2 Immunoassay	CS 3 Multistable	CS 4 Stem Cell	CS 5 Biophotovoltaics
	Collaboration process						
1	Designers' visualising of scientific processes, devices, principles, etc/tool for understanding and revealing tacit information			◉		◉	◉
2	Thorough evaluation of designers' ideas by scientists			◉			◉
3	Integration of feedback and joint design sessions			◉			◉
4	Early Involvement of the scientist in the design process (brainstorms)						◉
5	Participation of designers in some day to day scientific activity						◉
	Collaboration settings						
6	Clarity about the scope and limitations of collaboration, and the expected contribution of each disciplinary member of the team			◉			◉
7	Clear definition of project responsibility according to disciplinary abilities						◉
8	Involvement of 3rd parts moderating/feed backing/fostering collaboration		◉		◉		
9	None of the researchers closer than the others to a solution at the beginning	■					
10	Clear allocation of responsibilities	■	◉	◉	◉	◉	◉
11	Having a team leader or an altentative a work model in which decisions are taken by consensus	■		◉		◉	◉
12	Having "facilitator" to ease communication between members of the team	■	◉				
13	Initial added time for researchers' mutual knowledge and adaptation	■					
	Resources						
14	Provision of materials, equipment and space for designers' experimentation				◉		
15	Resources for design development costs		◉	◉			
16	Access to labs, people and information					◉	
17	Designer's ample range of skills / Right design skills for the project requirement		◉			◉	
18	Using socialising setting to discuss project			◉			
	Communication						
19	Intensive and constant communication			◉			◉
20	Scientists "de-technifying" language to the right level			◉			
21	Scientists extra efforts to explain scientific concepts to the designers			◉		◉	◉
22	Fundamental terminology established early and reviewed regularly	■					
23	Attention paid to unnoticed specialised use of same words that have different meaning in each discipline						
24	Developing a common language and making explicit the meaning of certain key words	■					

■ *Enablers of interdisciplinary collaboration as identified in chapter 5*
◉ *Enablers found in case studies*

Table 8.7 *Summary of enablers of collaboration between designers and scientists (1/2)*

Enablers of Collaboration Summary (2/2)

BLUE: Enablers clusters
DARK GREY: New enablers from case studies
LIGHT GREY: Known enablers

			CS 1 Mask Project	CS 2 Immunoassay	CS 3 Multistable	CS 4 Stem Cell	CS 5 Biophotovoltaics
	Attitude & Behaviour						
25	Active participation, engagement and time dedication		●	●			
26	Good will and enthusiastic attitude of scientists and designers					●	
27	Designers' proactive attitude to overcoming the scientific knowledge barrier			●			●
28	Recognition of disciplinary strengths and abilities			●			
29	Additional motivations different to the professional interest on the project topic		●	●			●
30	Being receptive, open minded , ready and proactive in learning from others, and having a sense of humour.	🟧					●
31	Personal empathy between researchers	🟧		●			●
	Approach & Method						
32	Research topics are equally interesting for all disciplines involved	🟧					
33	Reciprocity: Giving something back to the subjects studied by sharing with them the research developments and findings	🟧					
34	Parity: competing disciplinary points of view should be weighted by the team and balanced	🟧					
35	Agreement on measurement must be reached	🟧					
36	Reformulation of research problem inmediatelly done after an agreement on collaboration has been reached	🟧					

🟧 *Enablers of interdisciplinary collaboration as identified in chapter 5* ● *Enablers found in case studies*

Table 8.8 *Summary of enablers of collaboration between designers and scientists (2/2)*

8.6 What scientific research areas can design have an impact on?

In order to establish the scientific research areas upon which design can have an impact, this section takes designer contribution to scientific research and determines how it impacts on the three dimensions of scientific research - the social, the rational and the commercial.

With this purpose, the designer roles-tasks outlined in Chapter 8.3 and the contributions identified in sections 8.4, have been mapped on diagrams of the scientific research dimensions (developed from the collaboration matrix of Chapter 6), to determine which dimensions have been greatly impacted, and to determine in which aspects of scientific research design activity can play a major role.

In addition, this section compares the impact that design intervention has on scientific research according to what stage the research is at when design intervention occurs. To achieve this, designers' contributions are plotted in a table against the different stages of scientific research.

8.6.1 Design impact on scientific research activity according to designers' role-tasks

Different dimensions of scientific research can be affected in different ways by design intervention according to the designer role-tasks. As seen in Diagram 8.21, the expected impact of designer activity on scientific research is greater in its social and commercial dimensions, and lesser in the rational dimension. In the rational dimension there were 6 role-related task occurrences (9 counting occurrences repeated in 2 or more case studies), in the social there were 9(10) and in the commercial there were 11(14). This difference might be related to the specialised nature of the rational dimension of scientific research. As the work done by scientists in this dimension requires considerable scientific knowledge, designers may need to spend time and effort (which might not be possible) on preparation before being able to use their skills in a meaningful and useful way. In contrast, the social and the commercial dimension of scientific research involve activities and knowledge that are closer to the day-to-day experience of designers, and therefore they have more potential for design intervention.

It can be also observed that the designers' greatest contribution to scientific research is made while in the roles of *Scientific Research design support, scientific research application explorer* and *science visualisers and communicators*. This means that design can have an important impact on the manner in which scientists conduct their work, on the ways in which scientific research is applied, and on the mode in which science is represented and communicated.

The two roles in which designers' intervention seems to have the least impact are *design/science integrator* and *scientific research work/society & industry connections facilitator*. The low impact of the first might be due to the fact that design intervention need not necessarily lead to further collaboration with other designers, since design needs can be fully addressed within the collaboration team. Regarding the second, the fact that the most of the rational dimension of scientific research can be conducted within labs, relatively isolated from the public and society, may explain the lesser need for design intervention.

Design impact on scientific research according to designers' role (role-task) (Case studies results)

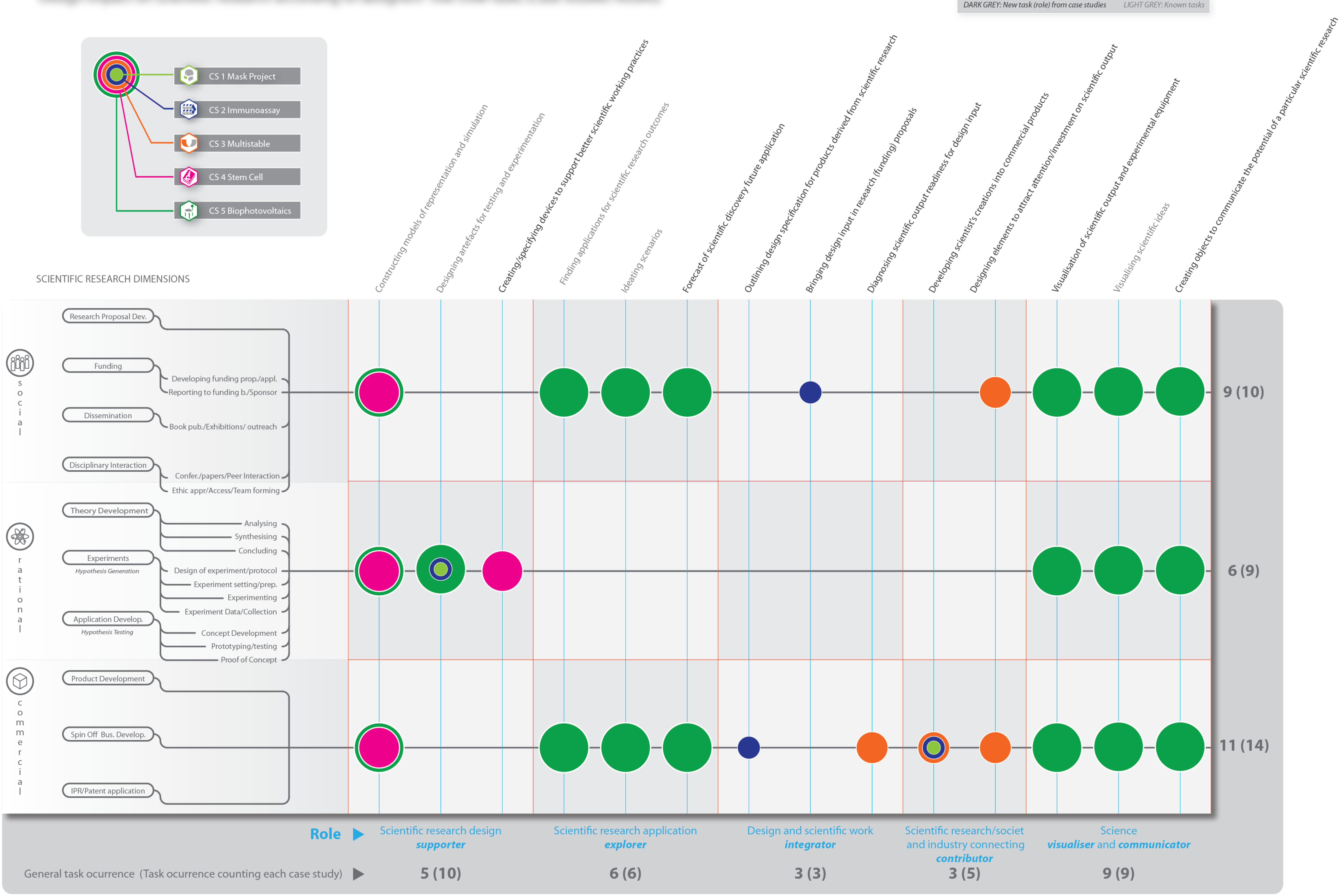


Diagram 8.21 *Design impact on scientific research according to designer roles (role-tasks)*

8.6.2 Design impact on scientific research activity according to designers' contribution

As shown in Diagram 8.22, the impact of designer contribution to scientific research is greater on its rational dimension than on its social and commercial dimension. Whilst in the rational dimension there were 18 contribution occurrences (39 counting occurrences repeated in 2 or more case studies), there were 9(10) and 11(25) in the social and commercial dimensions respectively. This contrasts with the design impact according to role-tasks explained in subsection 8.6.1. This disparity is probably due to the different focus on the analysis of the designers' roles by task and on the designers' contribution. Whilst the first makes reference to what was expected of the designers according to the constraints of a role definition, the second refers to what actually happened when designers and scientists collaborated. These results indicate that design intervention in scientific research has a wider scope than expected, and that they can equally contribute to all dimensions of scientific research.

It can be also seen that there are some scientific research dimensions that have not been impacted by some of the contribution clusters. This seems to be explained by the fact that those particular clusters are closely related only to specific dimensions of scientific research. For example, the cluster *Commercialisation of Scientific Research* seems to be strongly associated only with the commercial aspect of science. However, this lack of impact might be related only to the particularities of the case studies of this research. Further research will be necessary to understand if contributions related to these specific areas of science can be made in all dimensions of scientific research.

It can also be observed that there are four aspects of scientific research in which design has a greater potential for contribution: *Commercialisation of Scientific Research, Research Undertaking & Research Work Practices, Thinking in Scientific Research* and *Competencies for Scientific Research*. These areas show the wider variety of contribution forms: (15), (12), (14), and (27). This seems to indicate that design can play an important role in supporting scientists to commercialise their work, in influencing the ways in which scientific research is conducted, in influencing the way in which scientists think about their own research work, and in expanding the range of skills available to scientists for pursuing their research.

***Diagram 8.22** Design impact on scientific research according to designers' contribution*

8.6.3 Design impact on scientific research activity according to the stage of scientific research at the moment of collaboration

It seems that the impact that design activity has on the dimensions of scientific research is influenced by how advanced the research is at the moment of collaboration. In particular, the social and the rational dimensions appear to show greater potential for designer contribution when the research is in either its late or its early stages. As shown in the following table (8.23), there is a strong contrast between the number of contribution types in late/early stages, (6/6 in social dimension and 14/16 in rational dimension) and in the middle stage (1 in social dimension and 7 in rational dimension).

This may be explained by the character of scientific activity in these stages. In the early stages there is less certainty about the research subject and the research agenda and therefore more opportunity to introduce new thinking, whilst in the later stages the focus of the research may be directly linked with the development of applications and products (as in the Biophotovoltaics case study (early stage) or the Immunoassay case study (late stage)). Both circumstances seem ideal for design intervention: either introducing alternative ways of looking at issues in the early stages, or using design capability for the development of science-based products. By contrast, the middle stages of scientific research appear to be much more focused and convergent, with scientists trying to test previously discovered principles on the one hand, and attempting to apply these principles for specific and predetermined purposes on the other (as in the Mask case study). These middle stages are apparently less favourable for design intervention.

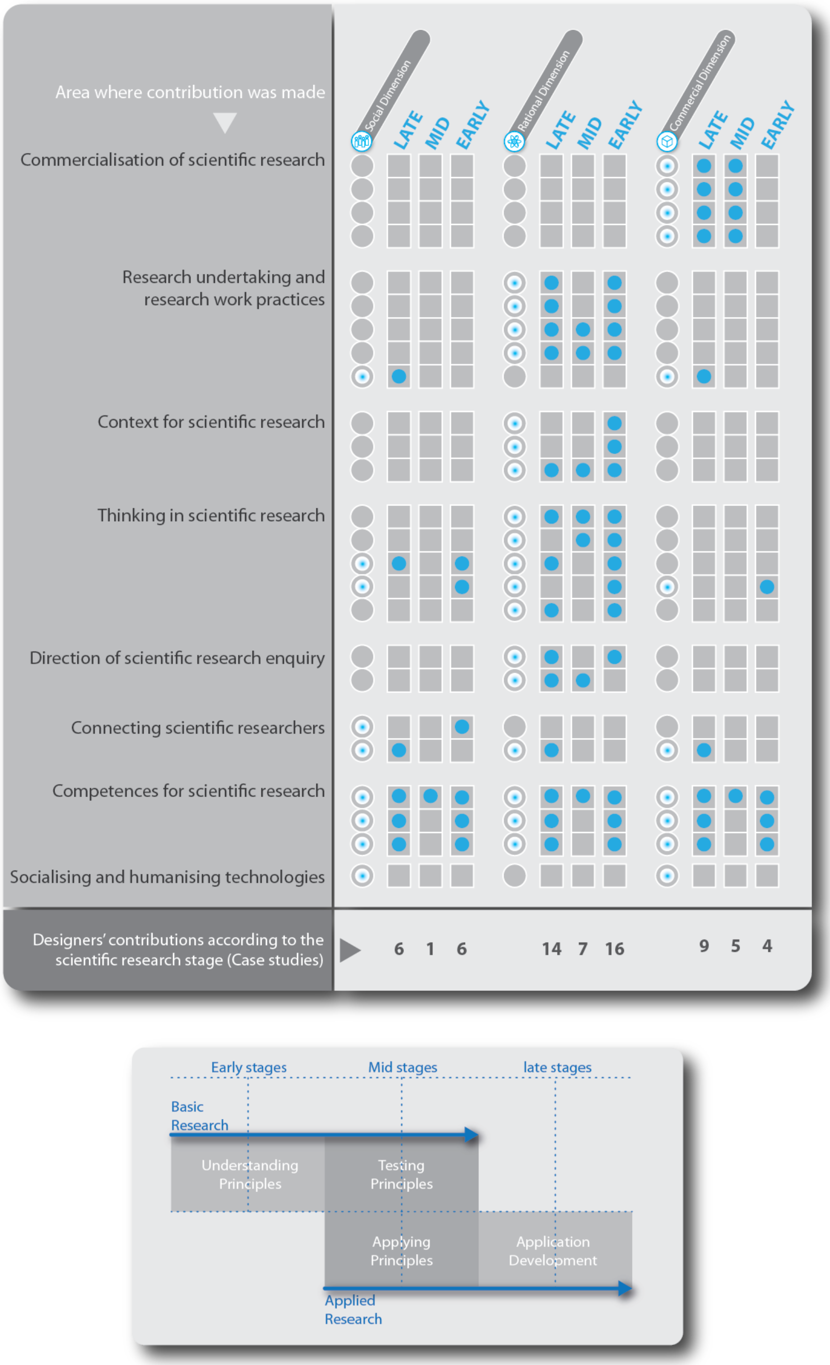


Diagram 8.23 *Design impact on scientific research activity according to the stage of scientific research at the moment of collaboration*

8.7 Summary and implications for the study

This chapter examines the case studies of this research project, with the purpose of answering the research question "*How can product designers and scientists collaborate and, as a result, how might designers contribute towards scientific research activity?*" by individually addressing its sub-questions:

- *What possible forms of collaboration can take place between designers and scientists in the context of scientific research?*
- *What role can designers have in scientific research while collaborating with scientists?*
- *What is the nature of the contribution that designers can offer to scientific research?*
- *What are the barriers to and enablers of such collaboration?*
- *What are the areas of scientific research in which designers can make an impact?*

The chapter starts by positioning the case studies in the process of scientific research, in either early, middle or late stages, indicating the research location and the initial and final research direction after collaboration, and evidencing that research activity occurrence was higher in the middle stages of scientific research.

The chapter continues by explaining each of the case studies' three main specific aspects of collaboration - Integration, Project control and Nature of activity, with the purpose of illustrating the ways in which the designers and scientists engaged. This also serves to address the question "*What are the different forms of collaboration that can take place between designers and scientists?*" Following this, the chapter demonstrates that the collaboration model developed in Chapter 6 is not entirely suitable for describing how designers engaged with scientists in the case studies. Therefore a new model is proposed. This model introduces 3 levels of collaboration in which designers act as Design Suppliers at the lowest level of engagement, as Design Consultants at the middle level, and as Team Researchers at the highest level of engagement.

After this, the chapter presents findings in relation to the research sub-question "*What roles might designers take in scientific research activity?*" It establishes that designers can have the role of technicians, experts or collaborators while engaging with scientists. However, these roles are apparently independent of the stages of scientific research in which designers intervene. The chapter also discusses that designers can play useful roles in scientific research, especially in helping to relate scientific work with society and industry, visualising and communicating science and connecting scientists' work with the world of design.

The chapter also examines the case studies with regard to the question "*What contributions might designers make to scientific research activity?*" It explains that contributions were made in eight different areas, and affected all three dimensions of scientific research.

The case studies are also individually examined in this chapter in relation to the question "*What are the barriers to and enablers of collaboration?*" As a result of this, summary tables are presented which integrate the barriers and enablers identified in the literature and in the case studies. The tables help to show how aspects such as collaboration settings and the personal characteristics and attitudes of designers and scientists, as well as communication between collaborators, are a major source of barriers. Similarly, the tables are useful in illustrating that some enablers relating to communication seem to be exclusive to collaboration between designers and scientists.

Finally, the chapter looks at the case studies aiming to address the question "*What are the scientific research activities upon which product design can have an impact?*" For this, designer contributions and role-tasks from the case studies and the literature are mapped onto diagrams of the three dimensions of scientific research. In this way it is possible to illustrate how designers can contribute to all dimensions of scientific research, and also to show how their contributions seem to have a prominent role in some specific aspects of scientific research. On the one hand, according to the designers' role-task, designers can influence the manner in which scientists conduct their work, the ways in which scientific research is applied, and how science is represented and communicated. On the other hand, in reference to their contribution, designers can have a major role helping scientists to commercialise their work, to improve their working practices, to think about their own research work in different ways and to expand their range of skills. The chapter also shows that design intervention can have greater impact in scientific research if it happens in its early or late stages (and less in the middle stages). This especially applies to the social and the rational dimensions of scientific research.

This chapter serves to address the research questions of this study by comparing and integrating the case study findings with the findings from previous studies by other authors, drawn from both design and interdisciplinary literature. As a result, new knowledge has been generated about collaboration between designers and scientists in the context of scientific research. These findings will be summarised in the following chapter of this thesis, which will also include a summary of the thesis and will explain its limitations, present a personal reflection, and illustrate possible and relevant future research.

9. CONCLUSIONS

This work presents the results of research examining collaboration between designers and scientists in the context of scientific research. In doing so, it examines extant literature and makes evident the scarcity of empirical studies on the subject, revealing that most studies are based on anecdotal evidence. It also identifies a knowledge gap in the subject and as a result formulates the main research question:

How can product designers and scientists collaborate and, as a result, how might designers contribute towards scientific research activity?

From this main research question, several research sub-questions are formulated:

- *What possible forms of collaboration can take place between designers and scientists in the context of scientific research?*
- *What role can designers have in scientific research while collaborating with scientists?*
- *What is the nature of the contribution that designers can offer to scientific research?*
- *What are the barriers to and enablers of such collaboration?*
- *What are the areas of scientific research in which designers can make an impact?*

With the purpose of establishing an analysis framework for the examination of collaboration between designers and scientists, this research also studies literature in three main areas: in the nature of both design work and scientific work (to underpin understanding of the work of designers and scientists engaged in collaboration), and also in interdisciplinary studies (to identify interdisciplinary aspects relevant to collaboration between designers and scientists).

This study also presents the results of three exploratory and two development case studies carried out to provide empirical evidence for the understanding of collaboration between designers and scientist in the context of scientific research. This study explains the origin and development of the collaboration, how the design process occurred and what the collaboration output was for each of the case studies. To achieve this, a collaboration matrix was developed and employed to make visible the interdependence of design activity and scientific research during collaboration, and to identify initial patterns, similitudes and differences between the case studies.

Then this study positions the case studies in relation to the process of scientific research, and presents its findings in response to each research sub-question.

The following sections will introduce the main contributions to knowledge of this study and present a personal reflection on the research. They will also explain the limitations of this study and will illustrate potential future work derived from this research.

9.1 Contribution to knowledge

Addressing the sub-question “*What possible forms of collaboration can take place between designers and scientists in the context of scientific research?”,* this research identifies for the first time three different forms in which designers can engage with scientists in the context of scientific research. In its less intensive form of collaboration, designers collaborate as *design suppliers*, remaining external to the research team, having a late involvement on the definition and development of the design project, and focusing effort on resolving design issues related to scientific research resources. In an intermediate form of engagement, designers collaborate as *design consultants*. In this form of engagement, designers remain external to the research team and focus on the resolution of resources for scientific research, but have an early involvement in the definition and development of the design project. In the most intensive form of collaboration, designers act as *team researchers*. On this level, designers act as members of the research team, are involved in the definition and development of the design project at an early stage and participate in the resolution of design issues related to both scientific research resources and scientific research questions.

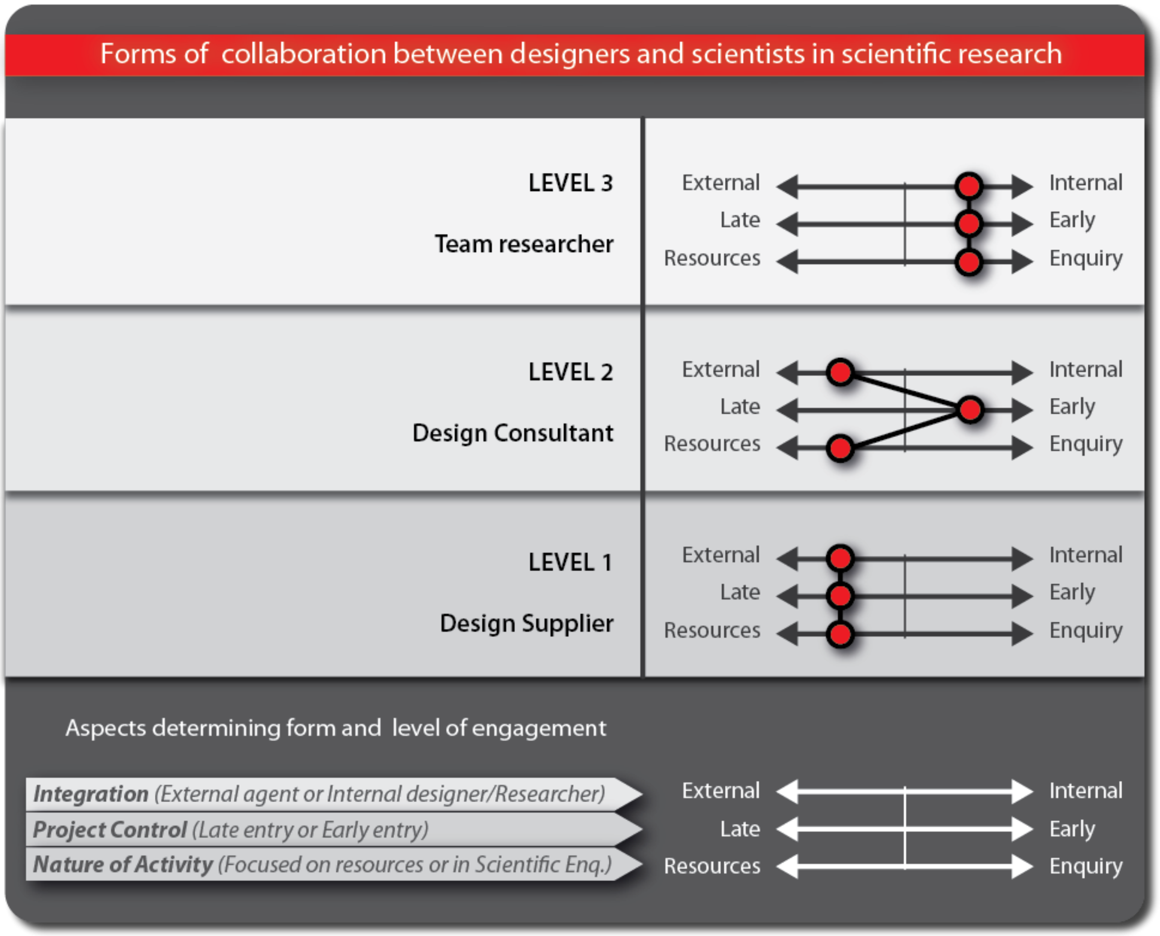


Diagram 9.1 *Forms of collaboration*

The second contribution relates to the question "*What role can designers have in scientific research while collaborating with scientists?"* This research identifies for the first time the roles that designers can have while collaborating with scientists in the context of scientific research in relation to the designers' involvement in the definition of the design problem, the proposal of the primary design concept solution, and the designers' point of entry into the design project (according to Paton & Dorst's (2011) role classification). This research establishes that designers can have the role of *collaborators* when they work with the scientists from the beginning of the project on identifying the design need and devising ways to address it. Also, they can act as *experts,* when brought to the project in the middle of its formulation when the scientists already have a partial idea of what is needed. Lastly, designers can have the role of *technicians*. This happens when the scientists already know what is needed and have a clear idea of what is required to address it. The designers are brought to the project after it has been formulated and execute the project according to the scientists' idea.

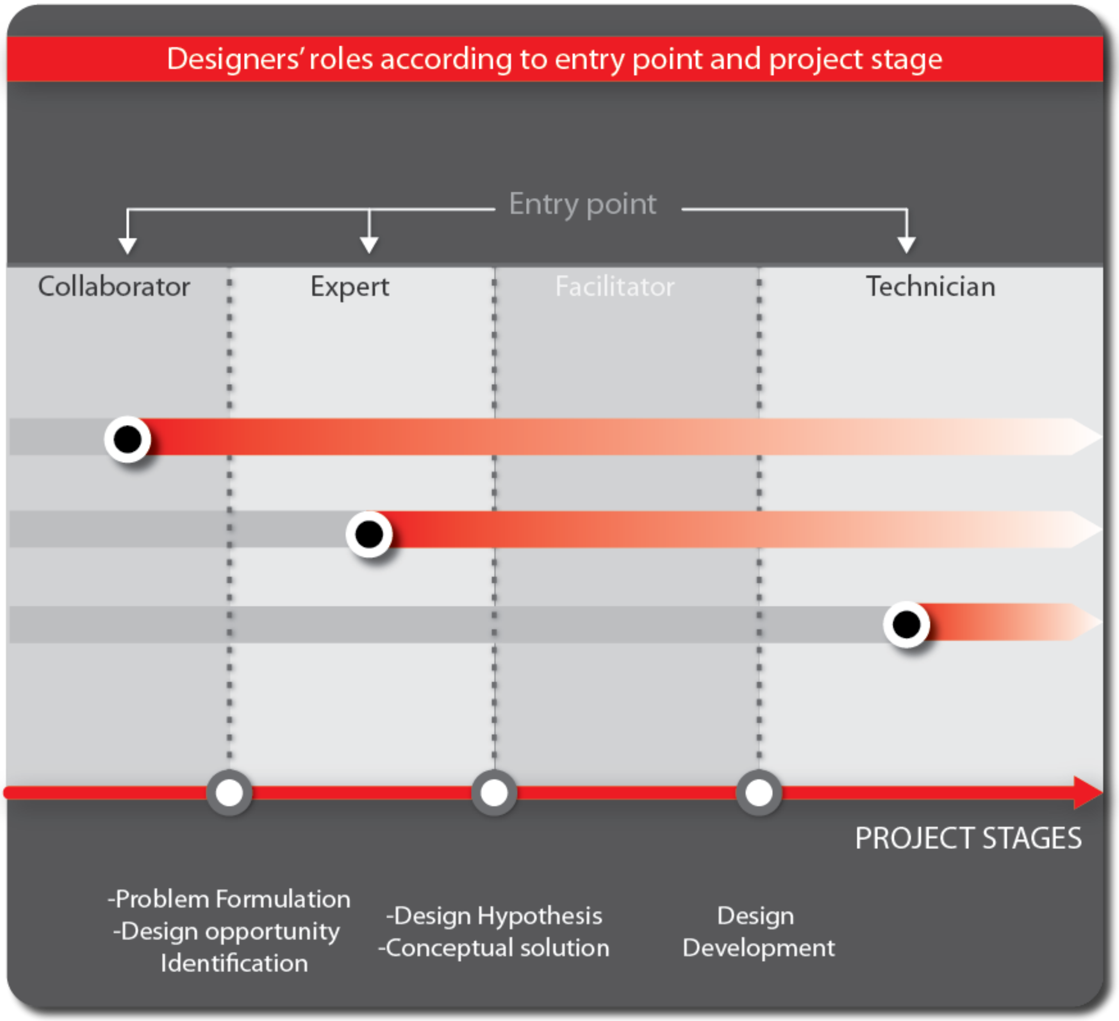
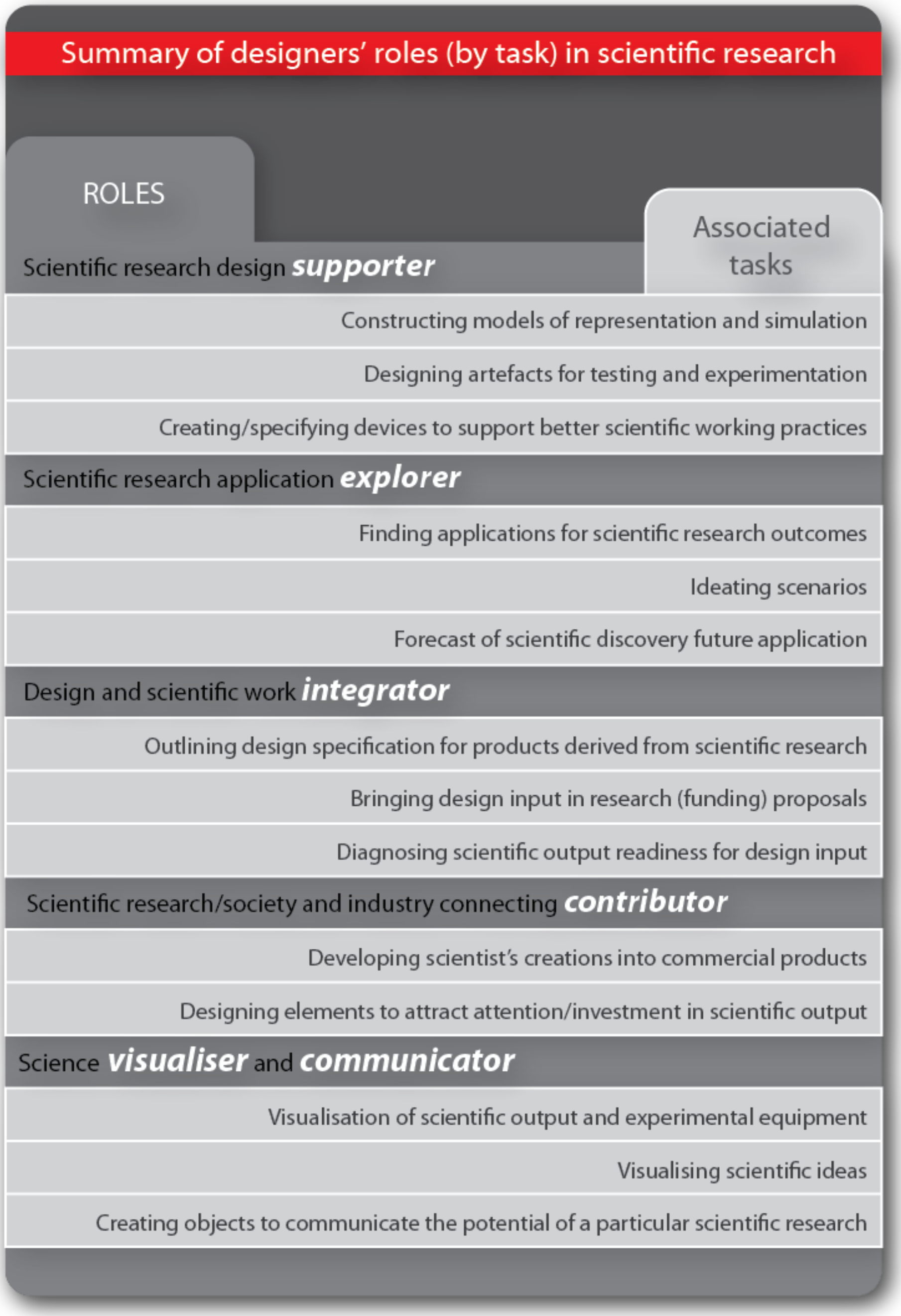


Diagram 9.2 *Designers' roles (entry point and project stage)*

This research has also contributed to knowledge by establishing what roles designers can have in scientific research according to the area of scientific research that is affected by the tasks designers are set to undertake (role-task). Table 9.1 shows the five different types of roles designers can have and the specific tasks associated to those roles.



Summary of designers' roles (by task) in scientific research

ROLES	Associated tasks
Scientific research design ***supporter***	Constructing models of representation and simulation
	Designing artefacts for testing and experimentation
	Creating/specifying devices to support better scientific working practices
Scientific research application ***explorer***	Finding applications for scientific research outcomes
	Ideating scenarios
	Forecast of scientific discovery future application
Design and scientific work ***integrator***	Outlining design specification for products derived from scientific research
	Bringing design input in research (funding) proposals
	Diagnosing scientific output readiness for design input
Scientific research/society and industry connecting ***contributor***	Developing scientist's creations into commercial products
	Designing elements to attract attention/investment in scientific output
Science ***visualiser*** and ***communicator***	Visualisation of scientific output and experimental equipment
	Visualising scientific ideas
	Creating objects to communicate the potential of a particular scientific research

Table 9.1 *Designers' roles (by task)*

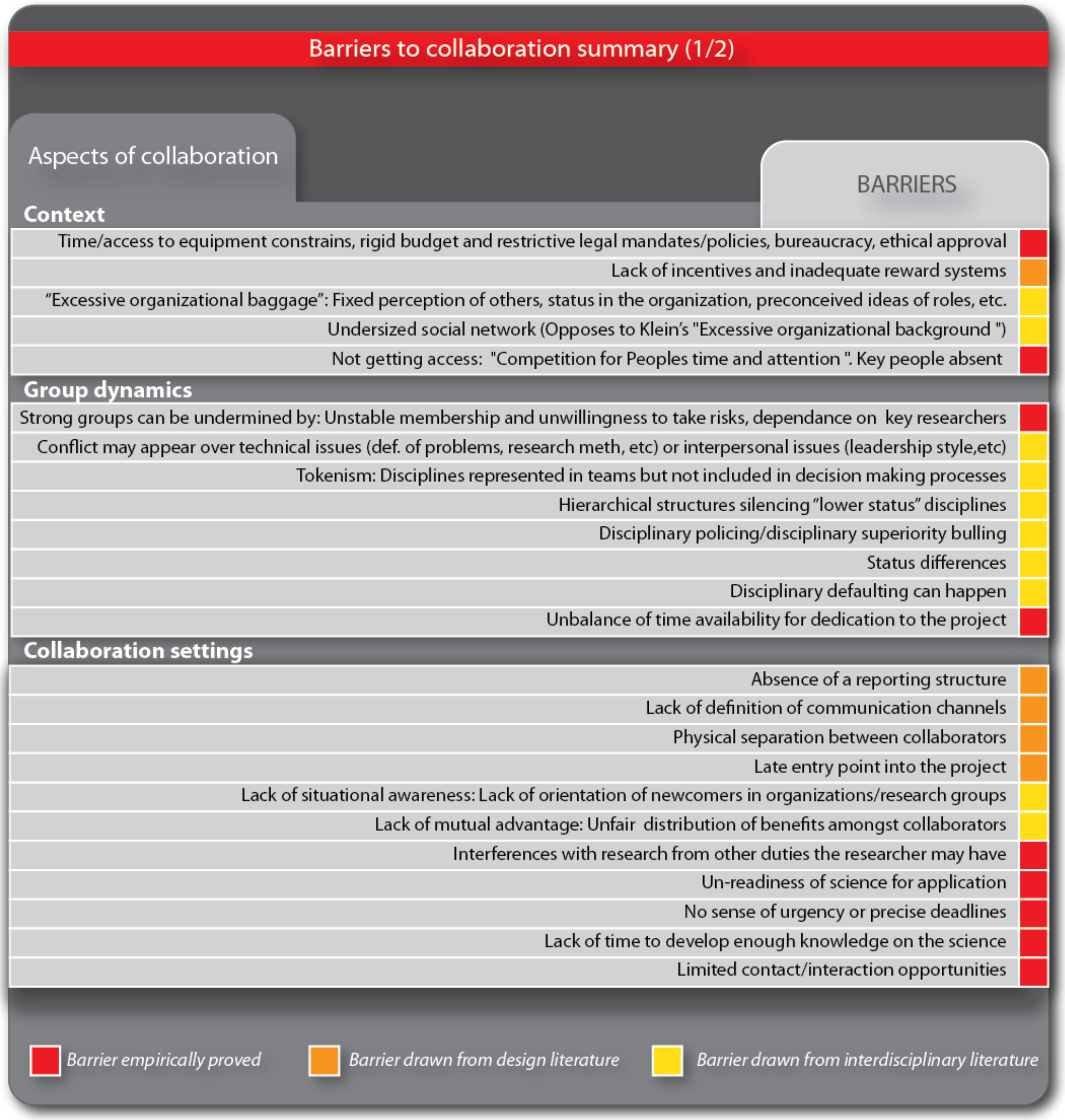
The third contribution of this research corresponds to the question "*What is the nature of the contribution that product designers can offer to scientific research?*" by presenting, for the first time, the different ways in which designers can contribute to scientific research while collaborating with scientists. Seven distinct categories representing those aspects of scientific research that can be affected by design intervention have been identified and used for grouping specific design contributions, as in Table 9.2.

Designers' contributions to scientific research

Affected aspects of scientific research	Contribution
Commercialisation of scientific research	
	Improving scientists' understanding on the gaps between their research inspired product ideas and a usable/commercial product
	Helping scientists to understand the technology level of readiness for design intervention towards commercialisation
	Supporting the development of scientific ideas towards future commercial application
	Supporting scientists to understand the functional and commercial potential of research output
Research undertaking and research work practices	
	Improving research lab working practices
	Creating/specifying means to support better scientific working practices
	Facilitating the advancement of scientific research, by providing means of experimentation and reflection
	Engaging in actual invention
	Supporting scientists in research funding and sponsorship applications
Context for scientific research	
	Repositioning of scientific findings into a new context
	Opening up new contexts for scientific enquiry and favours serendipity as a way for scientific discovery
	Providing a new context (design process) for the practice of scientific research
Thinking in scientific research	
	Bringing divergent thinking (Contrasting convergent)
	Providing lateral thinking about technology and science
	Prompting scientists' self-reflective attitude in regards to their working practices
	Challenging dominant structures in scientific research
	Unlocking "tacit" knowledge
Scientific research enquiry direction	
	Identifying possible new areas for scientific enquiry
	Challenging scientists' perceptions and encouraging the pursuit of new research directions.
Connecting scientific researchers	
	Connecting scientists with the non scientist, and helping to disseminate scientific knowledge amongst the general population
	Supporting scientists in dialogue with other external design/engineering collaborators
Competences for scientific research	
	Bringing disciplinary knowledge
	Bringing communication, design and project management skills
	Bringing visualisation skills for the communication and understanding of experiments, experimental equipment and research output
Socialising and humanising technologies	

***Table 9.2** Designers' contributions to scientific research*

The fourth contribution relates to the question "*What are the barriers to and enablers of collaboration between designers and researchers in scientific research?*" This research presents an unprecedented list of barriers to and enablers of collaboration between designers and scientists in scientific research. These barriers and enablers have been grouped in clusters related to specific aspects of collaboration. The following tables (9.3, 9.4 and 9.5) summarise them:

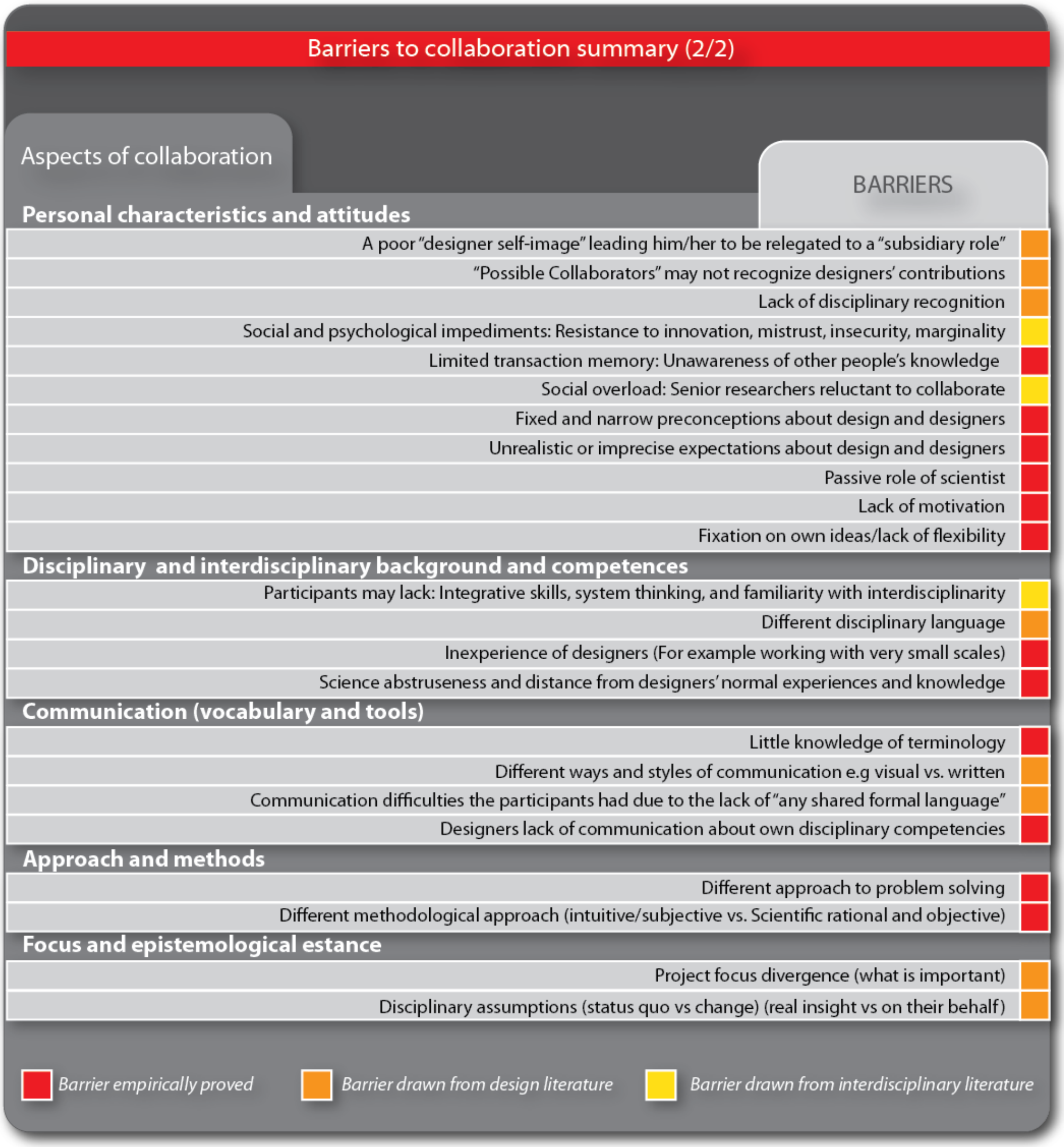


Barriers to collaboration summary (1/2)

Aspects of collaboration	BARRIERS	
Context		
	Time/access to equipment constrains, rigid budget and restrictive legal mandates/policies, bureaucracy, ethical approval	🟥
	Lack of incentives and inadequate reward systems	🟧
	"Excessive organizational baggage": Fixed perception of others, status in the organization, preconceived ideas of roles, etc.	🟨
	Undersized social network (Opposes to Klein's "Excessive organizational background ")	🟨
	Not getting access: "Competition for Peoples time and attention ". Key people absent	🟥
Group dynamics		
	Strong groups can be undermined by: Unstable membership and unwillingness to take risks, dependance on key researchers	🟥
	Conflict may appear over technical issues (def. of problems, research meth, etc) or interpersonal issues (leadership style,etc)	🟨
	Tokenism: Disciplines represented in teams but not included in decision making processes	🟨
	Hierarchical structures silencing "lower status" disciplines	🟨
	Disciplinary policing/disciplinary superiority bulling	🟨
	Status differences	🟨
	Disciplinary defaulting can happen	🟨
	Unbalance of time availability for dedication to the project	🟥
Collaboration settings		
	Absence of a reporting structure	🟧
	Lack of definition of communication channels	🟧
	Physical separation between collaborators	🟧
	Late entry point into the project	🟧
	Lack of situational awareness: Lack of orientation of newcomers in organizations/research groups	🟨
	Lack of mutual advantage: Unfair distribution of benefits amongst collaborators	🟨
	Interferences with research from other duties the researcher may have	🟥
	Un-readiness of science for application	🟥
	No sense of urgency or precise deadlines	🟥
	Lack of time to develop enough knowledge on the science	🟥
	Limited contact/interaction opportunities	🟥

🟥 *Barrier empirically proved* 🟧 *Barrier drawn from design literature* 🟨 *Barrier drawn from interdisciplinary literature*

Table 9.3 *Barriers to collaboration between designers and scientists (part 1 / 2)*



Barriers to collaboration summary (2/2)

Aspects of collaboration	BARRIERS
Personal characteristics and attitudes	
A poor "designer self-image" leading him/her to be relegated to a "subsidiary role"	🟧
"Possible Collaborators" may not recognize designers' contributions	🟧
Lack of disciplinary recognition	🟧
Social and psychological impediments: Resistance to innovation, mistrust, insecurity, marginality	🟨
Limited transaction memory: Unawareness of other people's knowledge	🟥
Social overload: Senior researchers reluctant to collaborate	🟨
Fixed and narrow preconceptions about design and designers	🟥
Unrealistic or imprecise expectations about design and designers	🟥
Passive role of scientist	🟥
Lack of motivation	🟥
Fixation on own ideas/lack of flexibility	🟥
Disciplinary and interdisciplinary background and competences	
Participants may lack: Integrative skills, system thinking, and familiarity with interdisciplinarity	🟨
Different disciplinary language	🟧
Inexperience of designers (For example working with very small scales)	🟥
Science abstruseness and distance from designers' normal experiences and knowledge	🟥
Communication (vocabulary and tools)	
Little knowledge of terminology	🟥
Different ways and styles of communication e.g visual vs. written	🟧
Communication difficulties the participants had due to the lack of "any shared formal language"	🟧
Designers lack of communication about own disciplinary competencies	🟥
Approach and methods	
Different approach to problem solving	🟥
Different methodological approach (intuitive/subjective vs. Scientific rational and objective)	🟥
Focus and epistemological estance	
Project focus divergence (what is important)	🟧
Disciplinary assumptions (status quo vs change) (real insight vs on their behalf)	🟧

🟥 *Barrier empirically proved* 🟧 *Barrier drawn from design literature* 🟨 *Barrier drawn from interdisciplinary literature*

***Table 9.4** Barriers to collaboration between designers and scientists (part 2 / 2)*

Enablers of collaboration summary

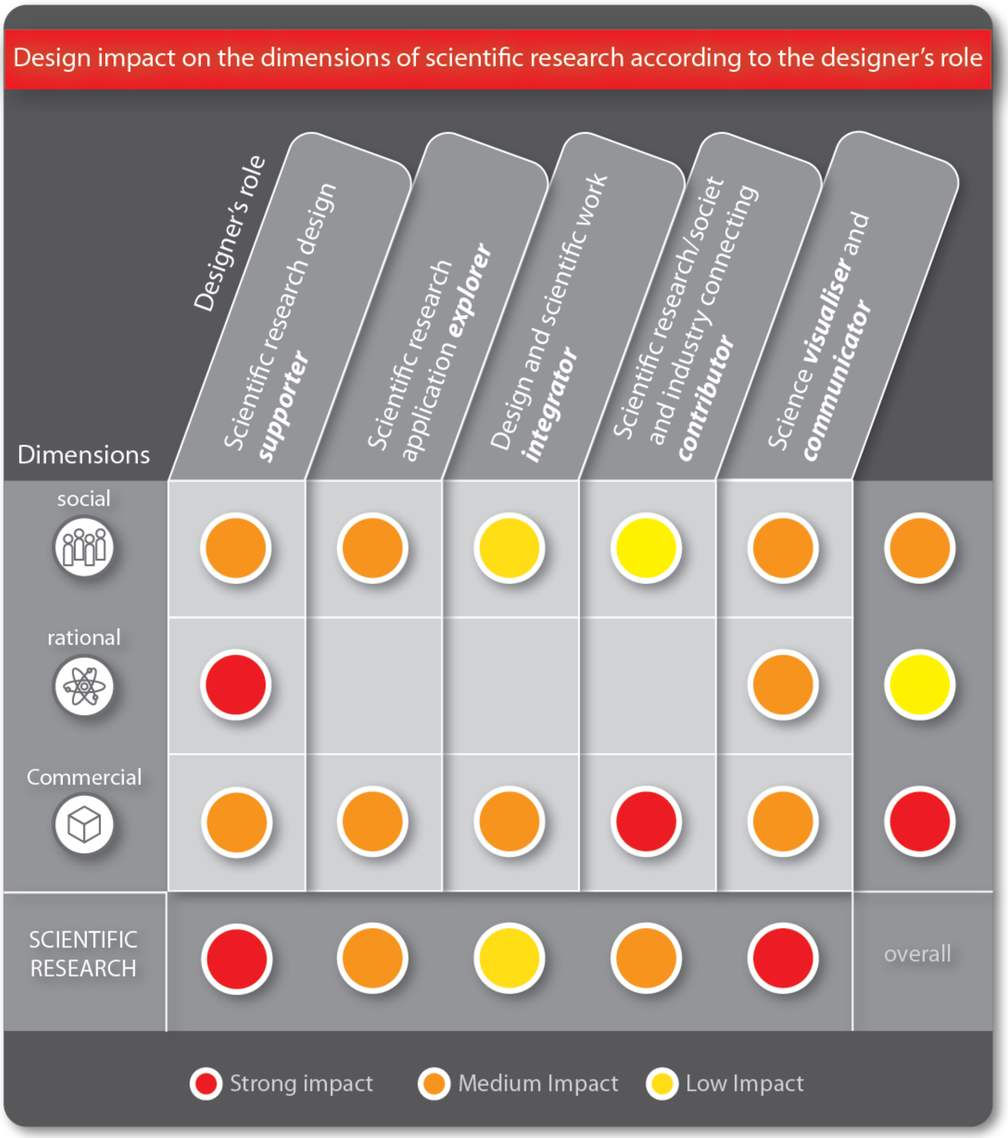
Aspect of collaboration	Enablers
Collaboration process	
Designers' visualising of scientific processes, devices, etc/tool for understanding and revealing tacit information	🟥
Thorough evaluation of designers' ideas by scientists	🟥
Integration of feedback and joint design sessions	🟥
Early Involvement of the scientist in the design process (brainstorms)	🟥
Participation of designers on some day to day scientific activity	🟥
Collaboration settings	
Clarity about the scope and limitations of collaboration, and the expected contribution of each member of the team	🟥
Clear definition of project responsibility according to disciplinary abilities	🟥
Involvement of 3rd parts moderating/feed backing/fostering collaboration	🟥
None of the researchers closer than the others to a solution at the beginning	🟨
Clear allocation of responsibilities	🟥
Having a team leader or an altenative a work model in which decisions are taken by consensus	🟥
Having "facilitator" to ease communication between members of the team	🟥
Initial added time for researchers' mutual knowledge and adaptation	🟨
Resources	
Provision of materials, equipment and space for designers' experimentation	🟥
Resources for design development costs	🟥
Access to labs, people and information	🟥
Designer's ample range of skills / Right design skills for the project requirement	🟥
Using socialising setting to discuss project	🟥
Communication	
Intensive and constant communication	🟥
Scientist "de-technifying" language to the right level	🟥
Scientists extra efforts to explain scientific concepts to the designers	🟥
Fundamental terminology established early and reviewed regularly	🟨
Attention paid to unnoticed specialised use of same words that have different meaning in each discipline	🟨
Developing a common language and making explicit the meaning of certain key words	🟨
Attitude & Behaviour	
Active participation, engagement and time dedication	🟥
Good will and enthusiastic attitude of scientists and designers	🟥
Designers' proactive attitude to overcoming the (scientific) knowledge barrier	🟥
Recognition of disciplinary strengths and abilities	🟥
Additional motivations different to the professional interest on the project topic	🟥
Being receptive, open minded , ready and proactive in learning from others, and having a sense of humour.	🟥
Personal empathy between researchers	🟥
Approach & Method	
Research topics are equally interesting for all disciplines involved	🟨
Reciprocity: giving back to the subjects studied by sharing with them the research developments and findings	🟨
Parity: competing disciplinary points of view should be weighted by the team and balanced	🟨
Agreement on measurement must be reached	🟨
Reformulation of research problem inmediatelly made after an agreement on collaboration has been reached	🟨

🟥 *Enabler empirically proved* 🟨 *Enabler drawn from interdisciplinary literature*

Table 9.5 *Enablers of collaboration between designers and scientists*

The fifth contribution relates to the question *"What are the areas of scientific research in which product designers can contribute?"* The research has identified for the first time, those areas of scientific research in which design intervention can have an impact. It has identified it in three different forms.

First, it has established how the dimensions of scientific research are affected by the different roles designers can have collaborating with scientists. The research suggests that the social and the commercial dimension of scientific research are most likely to be affected by a wider range of designers' roles. Also, it demonstrates that the rational dimension is strongly affected by designers playing the role of *supporters,* while the commercial dimension is affected by designers acting as *contributors*, and that designers have the strongest impact across all dimensions in their role as *supporters* and *visualisers/communicators.*



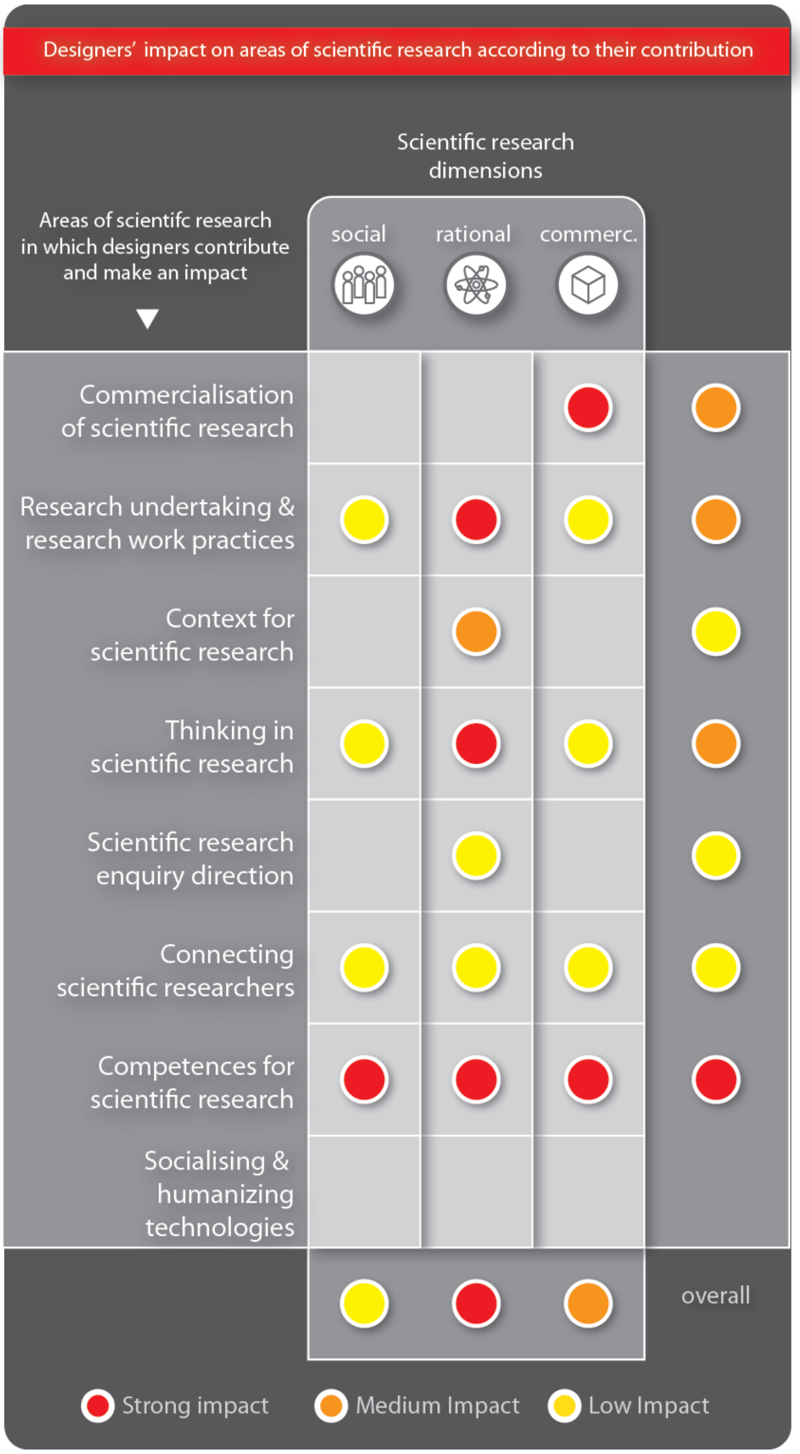
Design impact on the dimensions of scientific research according to the designer's role

Dimensions / Designer's role	Scientific research design **supporter**	Scientific research application **explorer**	Design and scientific work **integrator**	Scientific research/societ and industry connecting **contributor**	Science **visualiser** and **communicator**	
social	🟠	🟠	🟡	🟡	🟠	🟠
rational	🔴				🟠	🟡
Commercial	🟠	🟠	🟠	🔴	🟠	🔴
SCIENTIFIC RESEARCH	🔴	🟠	🟡	🟠	🔴	overall

🔴 Strong impact 🟠 Medium Impact 🟡 Low Impact

***Diagram 9.3** Designers' impact according to their role*

Secondly, it has identified the areas of scientific research to which designers can contribute, and how this contribution affects the dimensions of scientific research. The research demonstrates that there are eight main areas of scientific research in which design can make an impact, and that this affects all dimensions of scientific research.



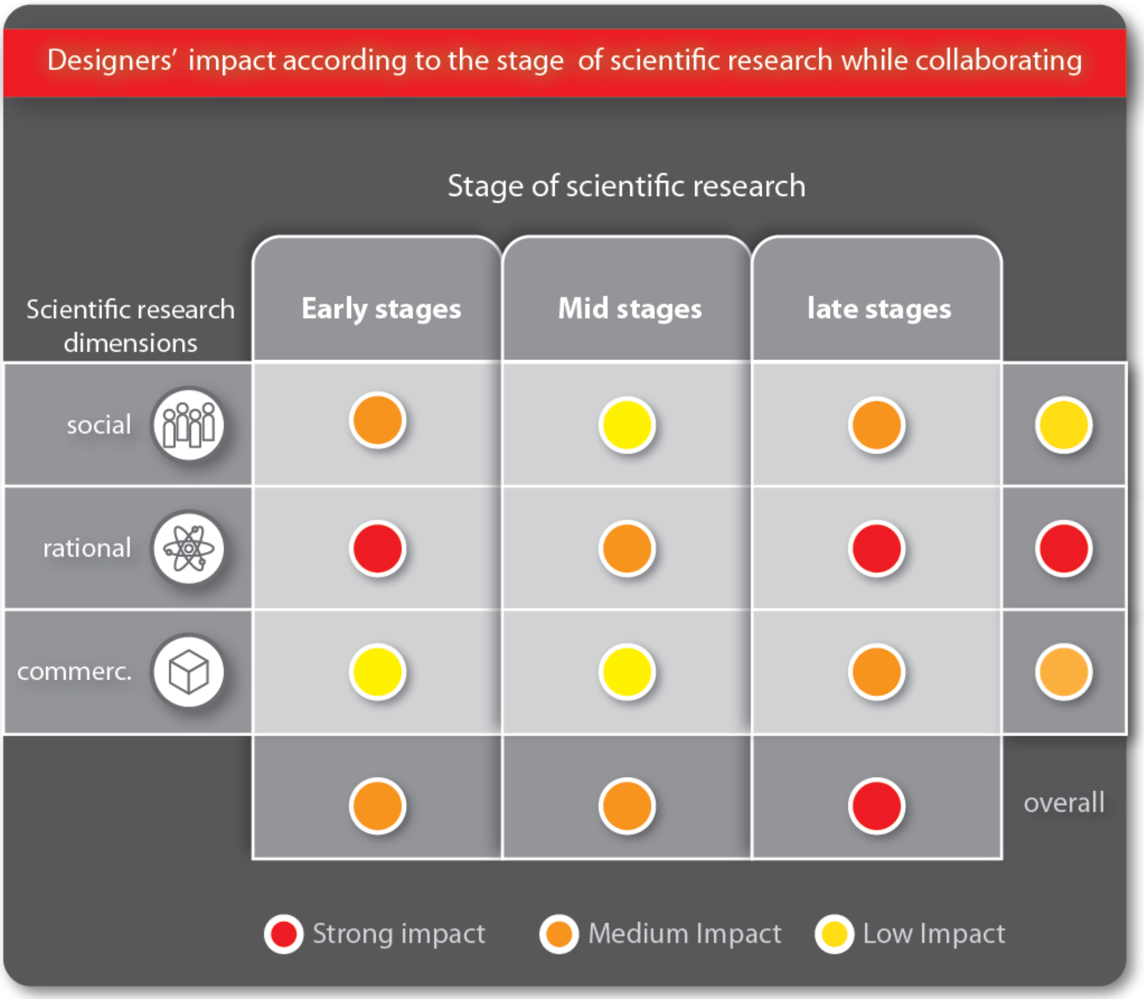
Designers' impact on areas of scientific research according to their contribution

	Scientific research dimensions			
Areas of scientifc research in which designers contribute and make an impact ▼	social	rational	commerc.	
Commercialisation of scientific research			🔴	🟠
Research undertaking & research work practices	🟡	🔴	🟡	🟠
Context for scientific research		🟠		🟡
Thinking in scientific research	🟡	🔴	🟡	🟠
Scientific research enquiry direction		🟡		🟡
Connecting scientific researchers	🟡	🟡	🟡	🟡
Competences for scientific research	🔴	🔴	🔴	🔴
Socialising & humanizing technologies				
	🟡	🔴	🟠	overall

🔴 Strong impact 🟠 Medium Impact 🟡 Low Impact

***Diagram 9.4** Designers' impact according to their contribution*

Lastly, the research demonstrates for the first time how design intervention affects the dimensions of scientific research depending on what stage the research is at when the collaboration with designers begins. It indicates that design intervention can have greater impact in scientific research if it happens in its early or its late stages, and this especially applies to the social and the rational dimensions of scientific research.



Designers' impact according to the stage of scientific research while collaborating

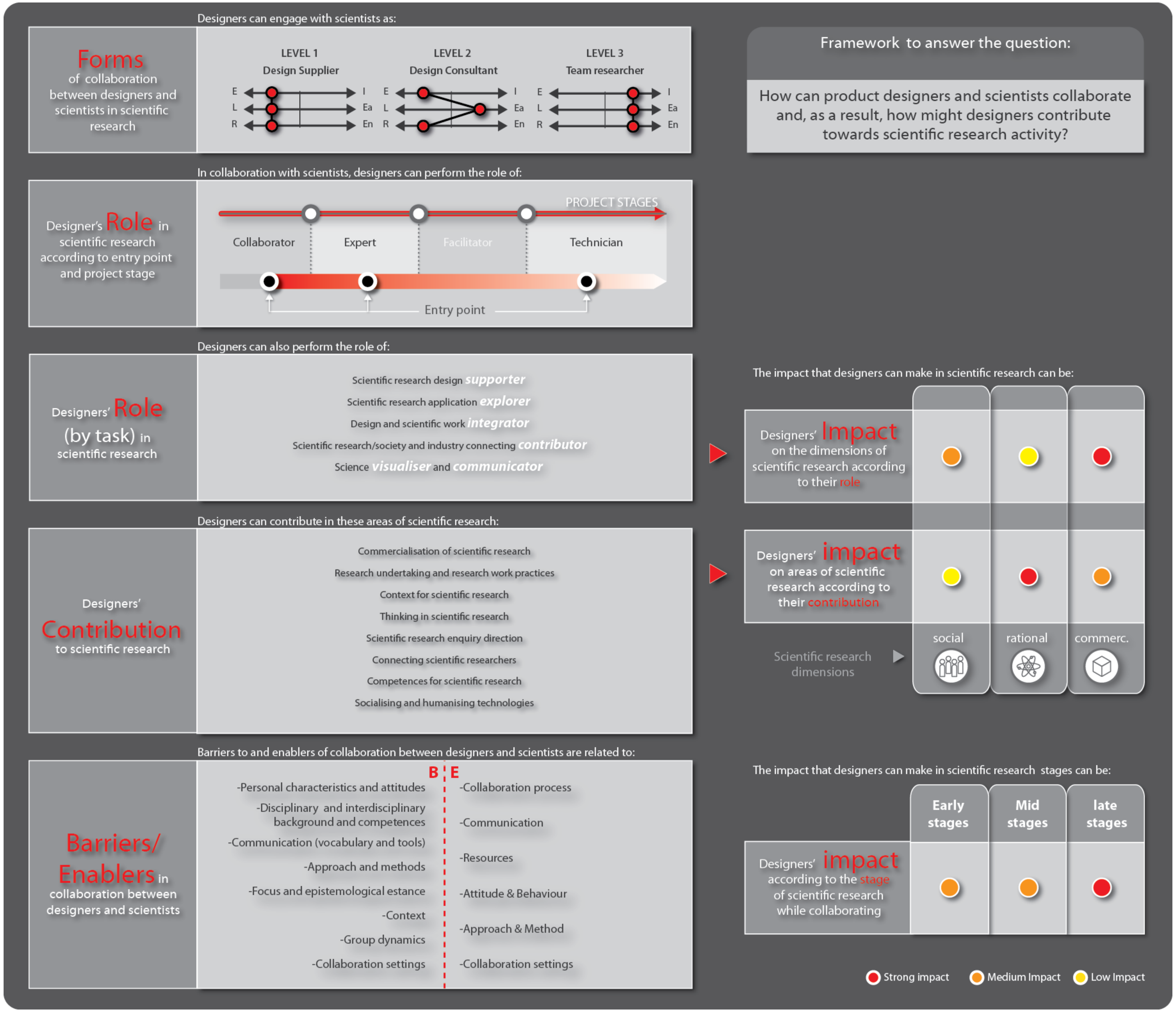
Stage of scientific research

Scientific research dimensions	Early stages	Mid stages	late stages	
social	🟠	🟡	🟠	🟡
rational	🔴	🟠	🔴	🔴
commerc.	🟡	🟡	🟠	🟠
	🟠	🟠	🔴	overall

🔴 Strong impact 🟠 Medium Impact 🟡 Low Impact

Diagram 9.5 *Designers' impact according to the stage of scientific research*

By answering the research sub-questions, uncovering the ways in which designers collaborate with scientists , identifying the roles that designers play in collaboration with scientists, explaining designer contribution to scientific research, outlining barriers to and enablers of collaboration, and revealing the impact that design can have in scientific research, this research proposes a framework that responds to the main research question *"How can product designers and scientists collaborate and, as a result, how might designers contribute towards scientific research activity?"* Diagram 9.6 represents this framework.



Designers can engage with scientists as:

Forms of collaboration between designers and scientists in scientific research

LEVEL 1
Design Supplier

LEVEL 2
Design Consultant

LEVEL 3
Team researcher

In collaboration with scientists, designers can perform the role of:

Designer's **Role** in scientific research according to entry point and project stage

Collaborator
Expert
Facilitator
Technician

Entry point

Designers can also perform the role of:

Designers' **Role** (by task) in scientific research

Scientific research design *supporter*
Scientific research application *explorer*
Design and scientific work *integrator*
Scientific research/society and industry connecting *contributor*
Science *visualiser* and *communicator*

Designers can contribute in these areas of scientific research:

Designers' **Contribution** to scientific research

Commercialisation of scientific research
Research undertaking and research work practices
Context for scientific research
Thinking in scientific research
Scientific research enquiry direction
Connecting scientific researchers
Competences for scientific research
Socialising and humanising technologies

Barriers to and enablers of collaboration between designers and scientists are related to:

Barriers/ Enablers in collaboration between designers and scientists

B	E
-Personal characteristics and attitudes	-Collaboration process
-Disciplinary and interdisciplinary background and competences	-Communication
-Communication (vocabulary and tools)	-Resources
-Approach and methods	-Attitude & Behaviour
-Focus and epistemological estance	-Approach & Method
-Context	-Collaboration settings
-Group dynamics	
-Collaboration settings	

Framework to answer the question:

How can product designers and scientists collaborate and, as a result, how might designers contribute towards scientific research activity?

The impact that designers can make in scientific research can be:

Scientific research dimensions	social	rational	commerc.
Designers' **Impact** on the dimensions of scientific research according to their role	🟠	🟡	🔴
Designers' **impact** on areas of scientific research according to their contribution	🟡	🔴	🟠

The impact that designers can make in scientific research stages can be:

	Early stages	Mid stages	late stages
Designers' **impact** according to the stage of scientific research while collaborating	🟠	🟠	🔴

🔴 Strong impact 🟠 Medium Impact 🟡 Low Impact

Diagram 9.6 Findings integrated into a single framework, explaining collaboration between designers and scientists in scientific research

In addition, this research has contributed to knowledge by the development of three methodological tools for the analysis of collaboration between designers and scientists:

- A collaborative matrix created to make visible how design and scientific research processes happen in the context of collaboration. The matrix makes possible the mapping of design and scientific activity, showing the sequence and frequency of such activities and the people involved (designers or scientists). It also makes possible the positioning of design and scientific activity in reference to the dimensions of scientific research and the stages of the design process. (Presented in Chapter 7, section 7.3)

- A visual model of scientific research that integrates basic research, applied research and application development. This model serves to locate scientific or design activity within the process of scientific research, as well as to identify research direction (presented in Chapter 5, section 5.3).

- A visual model of collaboration between designers and scientists. This model serves to determine the level of engagement between designers and scientists according to different criteria. The model allows the change or addition of criteria. For the present research the model utilises three main criteria: Integration, Project Control and Nature of activity (presented in Chapter 8, section 8.2.6).

9.2 Limitations of the study

This research has investigated collaboration between designers and scientists in the context of scientific research, contributing to academic understanding of the subject. However, it has potential limitations related to its scope and its methodology.

9.2.1 Scope limitations

As explained at the beginning of the study, this research is intended to apply only to product designers. Other designers such as graphic or interaction designers, who can also successfully collaborate with scientists, are not included in the study. The same applies to the scientists. Formal and social scientists have been left outside the scope of this study.

Also, this research has examined collaboration in research university settings. This research does not to apply to research conducted in commercial and industrial environments.

Additionally, this research has been conducted exclusively with scientists of the University of Cambridge, and undertaken within the university departments. It is acknowledged that specific contextual idiosyncrasies of the University of Cambridge may render some of the findings of this research non-applicable to universities with different characteristics.

9.2.2 Methodology limitations

The validity of this research has some methodological limitations since its findings are based on the subjective perceptions of the researcher about the phenomena studied, as well as the views collected from the case studies participants, which are also based on their own subjective views. However efforts have been made to increase the validity of this study utilising common methods in qualitative research as suggested in Ambert et al. [1995] and Adler & Adler [1994]. First, extensive and detailed descriptions of the case studies have been made based on a variety of data (videotapes, recorded interviews, recollection session with research participants) in an attempt to extend the author's own recollection of the phenomena studied. Secondly, the information collected has been member-validated with the participants (scientists and other researchers) to improve accuracy.

This research has also reliability (generalisation) limitations as the case studies under examination cannot be established as a representative sample, and therefore it is uncertain if the findings can be transferred to other cases of collaboration between designers and scientists. To address this, the study offers an extensive description of the way in which it has been conducted, so the reader can decide if its finding can be transferred to other settings or not. This also facilitates its replicability, in the sense that the same research methodology can be applied to similar research settings.

Lastly, while the range of the scientists participating in the cases studies was varied (7 scientists from 6 different sciences), there were only two designers. This means that the results of the collaborations in terms of design outcome have been strongly influenced (and limited) by the individual design capacity of the designers involved in the research.

The claims of this study take the form of *moderatum* which is a moderated generalisation that *"resemble the everyday generalizations of the lifeworld in their nature and scope, though it is possible to express them formally"* (Payne & Williams [2009]). These claims are moderated and do not attempt to apply to all circumstances and contexts, and have a hypothetical nature.

9.3 Personal reflection

During the case studies a number of observations were made. These observations should not be considered as findings but as subject-related themes for reflection. They can be considered as a reference for future research on the subject of collaboration between designers and scientists.

- *Motivation*

  This research has established that designer contribution can support scientists in relation to the commercialisation of their research output. However, from the case studies and informal interviews with scientists, it seems that pursuing the commercialisation of scientific ideas is not a desirable path for all scientists, because they may lack either interest in this type of activity or the resources or the expertise to pursue it. This situation points out an aspect that seems crucial to a successful collaboration: if both designers and scientists are not (equally) motivated, the chances are that collaborative efforts will not succeed.

- *Preconception*

  While conducting the case studies, it became clear that scientists sometimes have false preconceptions about designers' skills (and vice versa). Even though these preconceptions seemed to disappear as the case studies progressed, in some cases they remained until the end. It seems reasonable to assume that this situation can potentially hinder collaboration, and that action needs to be taken to address this issue.

- *Discovery vs. commercialisation*

  The case studies made it apparent that scientific work often combines basic and applied research, and that the boundaries between research for the sake of knowledge and research for commercialisation purposes can sometimes be blurred. Accordingly, specific designs can be developed either to aid research or to create commercial products. Although the main principles behind such goals might be similar, the outputs themselves are different and need to be designed in a different and separate ways. In these circumstances the scope and purpose of collaboration can sometimes be rendered unclear. It seems that special attention needs to be devoted to clarifying the purpose of the designs at the onset of collaboration, to ensure its success.

- *Contributing to the resolution of scientific questions*

  Scientists can spend their lives studying their research subject. They develop an understanding of highly complex phenomena that sometimes can be unintelligible to designers. Even though designers can potentially grasp the general principles of these phenomena in a relatively short time, further and deeper understanding would require much longer periods of study, and this is impractical within the normally limited time constraints of collaborative effort. For this reason it seems that the designers' ability to consciously contribute to certain aspects of scientific research (those related to the subject of study) might be rather limited. However, as observed in the Biophotovoltaics project, the longer designers and scientists spend working together, the smaller this knowledge gap seems. This learning process seems to be accelerated if the scientists have good communication skills and a good "teaching" attitude. It is apparent that designers' ability to make a purposely meaningful contribution to the resolution of scientific questions partly depends on the time available and the willingness and ability of both designers and scientists to overcome the designers' knowledge gap.

- *Compatibility of approaches*

  Designers and scientists approach problems differently. Scientists seem to commit to ideas on the premise that if they are well realised, they will work. If, after testing, they do not work, they are discarded and replaced with new ones. In contrast, designers seem to commit to ideas on the assumption that they will not work perfectly at the outset, but through testing and refinement they will eventually become a working solution. Scientists think about different aspects of a problem and seek a single solution that addresses all aspects of the problem at once. Designers look for a range of ideas that addresses the main problem but not every aspect of it. These differences in approach can create tensions between designers and scientists, but they are not necessarily counterproductive for the collaboration. As in the Photovoltaic project, if well managed such differences can boost the collaboration results.

- *The scale issue*

  Designers normally deal with objects of “human” scale. They can be handled and manipulated with no special skill. These objects have familiar “behaviours” according to people’s normal and day-to-day experiences. Designers have trade tools to make sketches, models and mock ups while designing these kinds of objects. However some of the objects that designers deal with while collaborating in scientific research are very small, sometimes microscopic. It seems that working in scientific research brings unusual challenges to designers and takes them out of their comfort zone. On the one hand, they cannot manually produce sketches and models because of the small scale, so they have to develop expertise in tools such as rapid prototyping. On the other hand, the “behaviour” of such small objects can be counterintuitive and can only be predicted if certain scientific laws are comprehended. For this reason, designers need to become knowledgeable in the relevant science beyond their layperson level.

- *Drivers*

  The Stem Cell project was the only case study in which the scientists became involved in the collaboration without a specific agenda. They were curious and open to collaboration but they did not have specific expectations of it. This was an apparent advantage for the designers, since they were free to choose any area of work according to their own preference and convenience. However, this lack of expectation by the scientists was also accompanied by low proactivity. Consequently the designers were left with complete responsibility for the work, the identification of problems and the proposal of solutions. It is apparent that for a successful collaboration it is better if both designers and scientists have a specific agenda and, as happened in most of the other case studies, if the needs are originally detected by the scientists.

- *Personality and empathy*

  Successful collaboration between designers and scientists depends on impersonal aspects such as clarity of objectives, adequate resources, etc. However the experience gained from the case studies indicates that good personal relationships and empathy between designers and researchers also affect it positively. As in some other observations made in this section, it is difficult to establish causality: is it the success of the collaboration that helps the participants to have a good relationship, or vice versa? However, it is clear that once the relationship is established, it helps to build trust and to make possible the use of informal channels of collaboration that otherwise would not be available, such as informal and unscheduled last-minute meetings, after-work discussion over drinks, etc. These channels can sometimes be more effective than formal ones.

- *Togetherness*

  In all case studies the amount of time that designers and scientists spend together varied. But it seems that the longer they spent together, the more fruitful the collaboration was in the end. However, it is difficult to establish if the collaboration was working because of designers and scientists spending more time together or if they spend more time together because the collaboration was working. But it seems clear that the more designers and scientists know about each other's work, the easier it is for them to work together. It is noticeable that the two case studies in which the scientists did not participate in design brainstorming sessions were the ones in which the collaboration seemed less productive (the Mask and Multistable projects). Conversely, the most successful cases (the Immunoassay and Biophotovoltaics projects) were those in which designers participated in (or witnessed) scientific activity and the scientist(s) took part in design sessions with the designers. So it seems that mutual knowledge of each other's work styles (and the time to develop it) is a crucial element in collaboration.

9.4 Future research

The results of this research (as well as its limitations) make it possible to think of potential new research directions and opportunities. With regard to this study's limitations, future research should examine a wider sample of collaboration cases to address potential issues of reliability. Having more cases to examine would make it possible to confirm (or refute) the consistency of the results.

Also, future studies should include a greater number of participant designers. In this way, possible validity issues can be addressed. An increased number of participant designers would guarantee that the results of the collaboration not only refer to the particular characteristics and skills of a few designers, but of a larger and more representative sample.

New potential research directions might include the following.

-Exploring collaboration between different permutations of designers from different design disciplines (graphic, interaction, interiors, etc) and scientists from different scientific backgrounds (natural, formal, social, etc):

The nature of the contributions, as well as the ways in which designers from different design disciplines might collaborate with scientists from different scientific backgrounds, might vary substantially according to their disciplines.

-Exploring collaboration between designers and scientists towards the common formulation and resolution of a research question:

The settings and dynamics of collaboration between designers and scientists might alter drastically, if they begin the collaboration with neither of them having evidently greater control over the research direction.

-Exploring collaboration between designers and scientists in commercial/industrial research contexts:

Differences between the working styles and rhythms of academic and industrial/commercial environments are widely recognised. The nature of collaboration between designers and scientists in such different contexts might therefore be substantially different too.

-Designers and scientists collaborating towards the resolution of scientific research questions:

The resolution of scientific research questions demands knowledge, creativity and resources. Would it be possible to team up designers and scientists so the scientists' knowledge and the designers' creative expertise can be integrated, overcoming disciplinary limitation, to successfully address scientific research questions?

Scientific research is fundamental for the development of science and its contribution to human development and wellbeing. Design has the potential to contribute to scientific research activity and to use creativity in the development and application of scientific output.

This research has demonstrated that collaboration between designers and scientists is a worthwhile and fruitful endeavour. Collaborative effort between designers and scientists not only results in the enhancement of scientific practice and the development of scientific output into useful products, but it helps to build bridges between scientists and non-scientists and can also steer scientific research in new and exciting directions.

Designers and scientists are very different professionals and collaboration between them can be sometimes challenging. It requires time, resources and the development of a common language and a trustful working relationship. Once these challenges have been overcome, collaboration can be a wonderful journey of discovery and creation.

FIN

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TRL	Technology Readiness Levels
SRL	Science Readiness Levels
HCI	Human Computer Interaction
UTTO	University Technology Transfer Officer
MCF	Micro Capillary Film
ELN	Electronic Laboratory Notebook
BPV	Biophotovoltaics
OECD	Organisation for Economic Co-operation and Development

Pages 409 to 420 include cover page and pages with roman numerals at the beginning of this thesis.