Mobilising materials knowledge: exploring the role of samples for supporting multidisciplinary collaborative design for materials development

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As designers increasingly become involved in larger and more complex multidisciplinary collaborations, they find themselves in unprecedented contexts of practice. New tools and methods are needed to support these challenging ways of working. This paper presents an ethnographic study focusing specifically on the role of materials samples in supporting knowledge sharing and mutual understanding in collaborative materials development. Observations are drawn from a case study of a 3.5 years EU H2020-funded multidisciplinary project which aimed to develop novel circular materials using a novel Design-Driven Materials Innovation (DDMI) methodology. Materials samples are known to be useful boundary objects for supporting the translation of codified scientific language into experiential language, which is essential for designers to understand materials potential. However, this study suggests that within the context of a complex collaboration, materials samples make knowledge available to all participants, and in particular, they appear to mobilise other forms of knowledge such as 'know-who', helping participants to understand the roles and capabilities of their fellow collaborators, enabling them to work together more effectively. This paper proposes a general framework identifying four types of materials samples used in the case study project, and their relationship to four forms of knowledge.

Keywords: multidisciplinary design, interdisciplinary design, design-driven material innovation (DDMI), materials samples, co-design, circular design

Introduction

Designers have long shown an interest in utilizing waste materials, perhaps motivated by a desire to minimize the impact of their practice by responding to an accessible and visible symptom of over-consumption. However, since the Circular Economy (CE) model was first popularised by the Ellen MacArthur Foundation (2013), design research strategies have evolved and advanced to operate in line with circular principles (Earley et al 2016; Hornbuckle 2018). Design roles and actions have emerged which seek to

deal with increasingly complex problems presented by the CE goals with a more systemic approach (Karell & Niinimäki 2019; Mononen 2017). Circular design research is not simply about using 'recycled materials', it is part of a multidisciplinary research field involving scientific LCA studies (Goldsworthy et al 2017), social research (Norris 2019), and alternative business models (Pederson et al 2019) in addition to looking at end-of-life solutions for products and materials. With this increased focus on collaborative working towards circularity, comes a more challenging environment for design practice. Being able to communicate effectively with other disciplines around the potential of different materials choices is seen as a significant advantage to this context of practice (Hornbuckle 2013; Goldsworthy & Ellams, 2019).

Tangible artefacts such as probes, toolkits and prototypes have been considered as vital to emerging codesign practices (Sandin & Stappers 2014). Materials samples however have a fairly unique set of characteristics due to their bridging capability between disciplines and their existing close relationship to design. Materials samples are used by designers both for inspiration and to understand the palette of materials available for a particular application. Having material options communicated in a tangible form is of particular importance for designers who operate at a greater distance from material making than, for example, an artist or craftsperson would, and also allows them to be able to access the ever-increasing number of novel materials that come to market, without 'knowing' them in greater depth (Wilkes et al 2015). However, the value of materials samples to designers and other disciplines involved in diverse teams co-designing materials – such as in the case study presented - is their ability to translate codified scientific materials information into "senseo-aesthetic" language (Miodownik 2007), or the language of experience (Karana et al 2015). This suggests materials

samples have the potential to support cross-disciplinary dialogue and mutual understanding to achieve collaborative goals.

This paper first explores the role of materials samples in relation to communication and knowledge-sharing within the multidisciplinary context before exploring the role of materials samples through the case study research. A general framework is finally proposed.

The importance of materials communication to design

There are a number of challenges in bringing together two or more different disciplinary fields to achieve the common goal of developing novel materials. Designers and technical experts operate using different forms of knowledge (Jensen et al 2017), have different working practices and methods (Pahl et al, 1999), work at different speeds (Niinimäki, 2018) and use different language when they communicate about materials (Ashby & Johnson, 2003). Enabling effective knowledge sharing during the multidisciplinary materials development process is an important task, which can be supported by using materials samples as part of a broader materials communication strategy.

The study of materials communication is a relatively new area of research concerned primarily with how people comprehend, understand and communicate about materials. This has been of increasing importance with the emergence of numerous novel materials which are unfamiliar to those who might apply, utilize, make with, or use them, for example designers (Wilkes et al 2015; Hornbuckle 2012; 2010; Manzini, 1986;). There are additional motives for improving materials communication and therefore making a broader range of materials more accessible to design. There is often an economic motive to speed up the time to market of new technologies (Tubito et al 2019; Verganti 2009), and sometimes a moral imperative to shift from less abundant

materials to more abundant materials or materials with improved characteristics for sustainability, circularity or health (Hornbuckle 2010).

Materials samples have received a great deal of attention in multidisciplinary research, for example Miodownik (2007) and Laughlin (2008) have been interested in how young's modulus is perceived by an artist or designer in descriptive or aesthetic terms (Miodownik, 2007:1629); how the numeric value relates to the touch, taste or feeling of that material (Laughlin et al 2008). Kerana has articulated this form of tacit knowledge of the material as 'material experience' (Karana et al 2015), and considers the need for play and touch to know the material potential and affordances. Nevertheless, materials samples and collections are seen as a powerful tool for fostering materials understanding between disciplines and the focus of the research in this field to date has been to understand in what forms and organisations materials samples can meet the various challenges of mutual materials understanding (Barati & Karana 2019; Wilkes et al 2015; 2011).

Ways of thinking about the role of materials samples

Wilkes et al (2015) and Miodownik (2007), draw on Star & Griesemer's (1989) theory of 'boundary objects' to describe materials samples as a means of anchoring cross-disciplinary dialogue. For example, in light.touch.matters, the 'sister' DDMI project to T2C, Wilkes and Miodownik developed a 'design-led materials development online course' which encouraged the use of materials samples as boundary objects to help establish a materials language between disciplines at the beginning of the project, to sustain a meaningful and effective collaboration through the development of the material. In this scenario the material sample's role is as a reference point to enable more effective dialogue (Akin & Pedgley 2016), which in some instances will help

collaborators to learn how to communicate by mutual translation of meanings behind key descriptive terms.

In this way materials samples can play a central role in enabling knowledge sharing between disciplines with very different languages and communication styles. Innovation management provides an interesting theoretical framework for the different types of knowledge and learning imperative to technology development and innovation. Jensen et al (2007) posit the four forms of knowledge as being particular to two modes of learning: 'know-what' and 'know-why' being particularly related to scientific learning and innovation, whereas 'know-how' and 'know-who' are more associated with experience-based and applied practices such as design. Jensen suggests that making tacit knowledge explicit and vice versa is one of the key areas where tensions can arise between the two modes. This framework can begin to explain the importance of materials samples as they reconcile codified and tacit knowledge within one tangible form; the dialogue and discussion resulting from mutual interaction with the sample makes the tacit knowledge explicit and the codified language tangible, becoming transportable embodied knowledge (Ibid. 2017:682). Within a new collaborative team, the 'know-who' dimension is particularly valuable as it allows people to understand who to work with on different tasks and develop a sense of their own position and others' within the project process (Gilley et al 2010).

Akoglu & Dankl (2019) argue that mutual learning and understanding can be a central outcome of a participatory co-creation design research approach, building empathy amongst stakeholders when workshops are structured on "openness, interactivity, interpretation, inspiration and engagement." (ibid:9). The case of Trash-2-Cash could be considered as a systems approach to materials development where an attempt has been made to represent the (technological) material life cycle system within

the consortium partners. Mononan (2017) presents a systems perspective on the challenge of co-creation, arguing that collaborators in the system may have different worldviews, yet “preferable respect for and understanding of the ways of knowing in other disciplines could bring them to a more rigorous and productive cooperation, clarifying the understandings, values and boundaries between the fields.” (Ibid: 4350). While materials samples have been considered as dialogue-enabling between participants, they have not been considered within the framing of a system. Materials samples have the potential to enable participants to make explicit their own worldview and understand those of others, perhaps therefore lifting the gaze from siloed knowledge to systems knowledge, enabling co-creation of outcomes that become ‘more than the sum of the parts’, greater than the individual expert contributions.

Mononan’s work brings to mind the ‘demonstrator sample’ which has emerged in design research as crucial to collaborative materials development. During a seminar, where designer-scientist partnerships were invited to discuss their tactics for collaboration during collaborative materials development, ‘material demonstrators’ emerged as a central tool in the iterative process “as a way of allowing others to see what is possible” (Hornbuckle 2017:3). Furthermore Barati & Karana (2019) highlight the importance of material demonstrators for supporting shared understanding of what is possible, based on their experiences of collaborating in the light.touch.matters DDMI project.

Making materials knowledge available

Within materials consultancy (the commercial arm of the materials communication field) materials samples are not used in isolation, they are part of a system of materials communication tools, methods and events which help to support and disseminate knowledge to wider audiences (Akin & Pedgley 2016; Hornbuckle 2013). Materials

samples can be seen to be related to a number of other types of material information provision: materials sample libraries, online catalogues, consultancy services, trade shows, media and events, and involving a range of communication tactics: materials property data, dialogue, images and written description. How materials samples are organized and linked to a system of supporting information is one way of making knowledge accessible to collaborators and within the limitations of time and location mentioned previously. While the faciliatory element of materials communication observed within Trash-2-Cash as part of this study has been presented elsewhere (Hornbuckle 2018), it is important to acknowledge this essential characteristic when considering the role of materials samples. The benefit of a materials library as a tool for supporting cross-disciplinary materials communication relates to the way the materials are categorized or framed by information providers.

Introducing the case study: Trash-2-Cash

The case study presented relates to Trash-2-Cash (T2C), a 3.5 year Design Driven Material Innovation (DDMI) project funded by the European Commission (grant number 64622). The disciplines involved in the project included industrial design, garment design, design research (theory & practice), manufacturing, social science (consumer behaviour), life cycle assessment, textile-sorting and recycling as well as material science, research and development, represented by 17 partner organizations. Participants were given the opportunity to be involved in the early development of circular materials through the lens of design: the recycling of textile waste into a polyester fibre and a cellulosic fibre for textiles and garments; a polymer for injection moulding and a reinforced plastic (composite) material for automotive parts. Conversations around materials were central to this collaboration, and the involvement of a materials library as a strategic project partner meant that material samples

themselves were posited as an important communication tool. However, participants were not only challenged with understanding the potential of a given material sample, but also tasked with imagining the potential of a material that doesn't yet exist (Niinimaki 2018).

There has been a significant body of research exploring aspects of the overarching Trash-2-Cash project methodology (i.e. Hornbuckle, 2017, 2018; Niinimaki, Tanttu, Kohtala, 2017; Niinimaki, 2018; Earley & Hornbuckle, 2018). The purpose of this paper is to analyse the role of materials samples within the case to discover what types of information or knowledge the materials samples are able to mobilise between disciplines and towards mutual understanding and effective collaboration.

The T2C collaboration was facilitated through twelve co-design workshops involving representatives from each partner organisation. These and the process flow were coordinated, debated and designed by a methodology team comprising representatives from the main disciplinary areas and led by the lead materials facilitator (a consultant from the commercial materials library). The team held conference call meetings two to three times in between workshops to discuss how the next steps could be facilitated, using which tools, methods, workshops sessions and tasks. The process was exploratory with the ongoing ethnographical design research and insights from the methodology team feeding the planning of the next steps. The author was positioned within one of the academic partners alongside textile design researchers and was a member of the methodology team, responsible for the task of capturing and analysing the Design-Driven Material Innovation (DDMI) methodology.

Methods

The case of Trash-2-Cash presented the opportunity for materials communication methods such as the use of materials samples and their supporting framework, to be observed and investigated within a unique collaborative materials development project. Very little was known at the outset of the project about how the role of materials samples might change within this novel context; therefore, an ethnographic approach was taken. Curtis & Curtis (2011) describe ethnography as a very fluid approach where "the researcher is unlikely to know all of the variables of interest before she begins the research, and variables may be changed and added as the research progresses." (Ibid:87). Furthermore, "participant observation is the key research method" (Ibid:87) and can be supplemented with additional data collection, which adds to the validity via triangulation (Costa, Patricio, & Morelli 2018). Case study research was considered an appropriate methodology given that the project presented a unique situation where participants in defined groups could be studied "to understand complex phenomena" (Yin 2018: 3). Furthermore, case study research allows for the researcher "to focus in-depth on a 'case' and retain a holistic and real-world perspective." (Ibid:3) which suited the intention of the research; from the messy nature of real-world collaboration new practices emerge to form a holistic view of the value of materials samples for future design processes.

The ethnographic methods included observing the interactions within the workshops, recording audio, taking detailed field notes and photographs. Table 1 details the datasets collected during the 42month period of the project. In addition, interviews were conducted at two significant points in the project. The first round of interviews was conducted with the facilitators of the first 'design request' to materials R&D during the early stages of Phase 2, after workshop 6. These interviews add detail around the role of the different materials during the crucial 'gap' phase when ideas were being

translated into decisions. The second round of interviews were conducted in the latter stages of Phase 3 to allow participants to reflect on the key challenges within the project.

Table 1. Datasets collected for the Trash-2-Cash case study

Main datasets	**Reference within the paper**	**Analysis**
12 x workshop observation data: • Workshop schedules; • Field notes, • Photographic images; • Worksheets; • After-action reviews (AARs)	WS01-Obs WS02-Obs Etc.	Visual analysis of samples use in photographic data; Macro- analysis to reveal themes in process from field notes, worksheets and AARs)
4 x interviews with Materials Liaison Officers (people identified to facilitate materials communication)	TechMLO-1 (Technical) DesMLO-1 (Design)	Themes developed by observation and literature review, coded, (presented in detail in Hornbuckle 2018)
8 x interviews with Designers and experts involved in Design Specification process 1 x interview with cluster leader	DesDSP-1 (Designer) TechDSP-1 (Technical Expert) EvalDSP-1 (Evaluation Expert)	Themes developed by observation and literature review, coded.

The organization and coding of photographic and interview data proved to be particularly useful for inductive reasoning and iterative analysis of the 'role of materials samples'. In total 2805 photographs were taken by the design researchers over the course of the 12 workshops giving a mean average of 234 per workshop. These were reviewed for unique instances of material sample use. Figure 1 shows part of the visual analysis of the final selection (114 photographs) which was then coded for a) types of samples being used and, b) the role or purpose of the sample. The visual display of the

photographs and the coding process facilitated sense-making during the analysis phase. Grady (2008:4) states that “Photographic data provides a more direct record of the actual events being investigated than any of the other major forms of data collection used by social researchers.” Grady considers that the frame for interpretation is equally if not more important than the intent of the photographer. This relates to Byers’ (1964) claim that when photographs are viewed in reflection, being literate in a particular frame of reference (in this case the role of materials samples in cross-disciplinary communication) can lead the researcher to ‘event-discoveries’ ‘that are important to them but which they did not see at the event they photographed’ (Ibid:80). In turn this process enables patterns to emerge which would not be visible to the researcher otherwise.

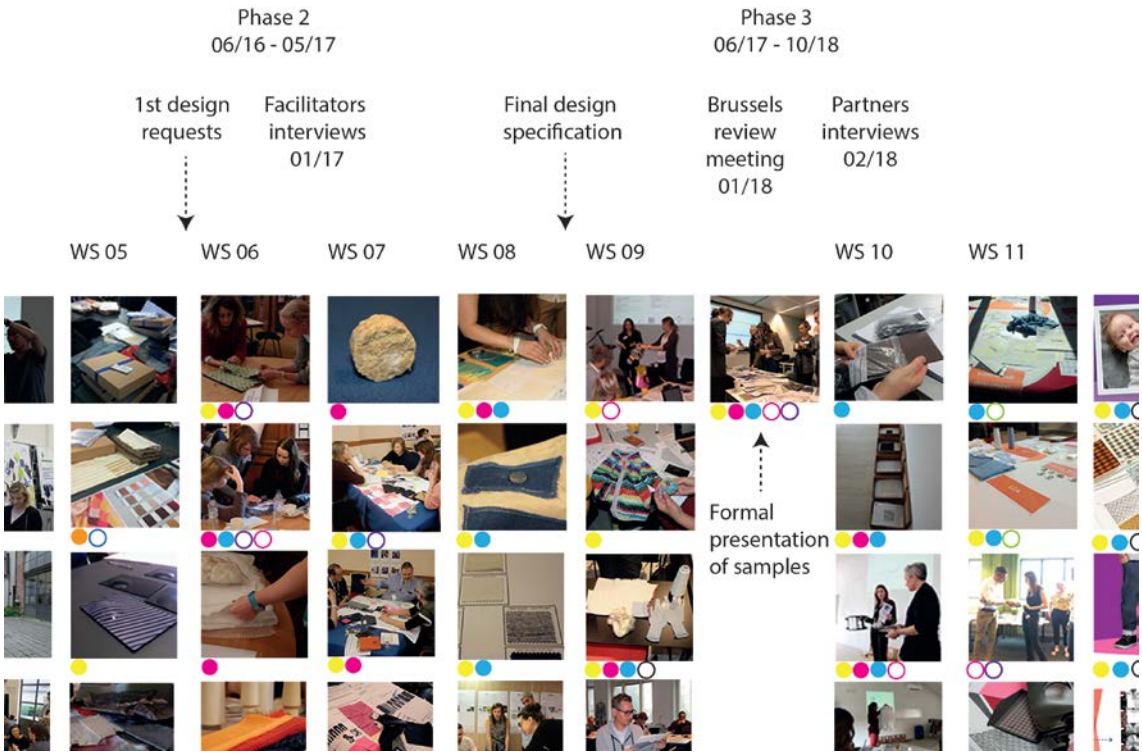

Figure 1: Close-up section of the visual analysis of photographic data, coded and with key moments added

The interview data provided alternative perspectives on the role of materials samples and the challenges to mutual understanding that different partners experienced. The analyses were cross-referenced to build theory around how the materials samples might have better supported the collaboration if approached differently.

The role of different material samples in the case study

The analysis and reflections of the empirical data are presented here in relation to the four types of materials identified in the case study. These findings are then used to inform the development of a general framework.

The four sample categories defined relate to the context within which they were produced. This is seen as the most appropriate way to differentiate the sample groups because it defines the type and availability of information and knowledge embodied by the sample. The sketch mapping in Figure 2 shows the primary location of the different sample types within the three-phase co-design process of T2C.

Pre-project samples

For the first workshop, the materials R&D partners were asked to bring samples of the material research they had conducted prior to the project. These included fibres, yarns and textiles and were used to explain the technologies under development. At this early point in the project these were the only samples available; they provided an important starting point for thinking through the potential of the technologies for all partners, not only the designers. From questions raised at the open discussions in subsequent workshops it is apparent that at this point each participant was viewing these materials through their own lens (Mononan 2018), resulting in the formation of a myriad of varied questions from different perspectives in the room. Mononan (2018) suggests that when collaborators begin to learn about how their own lens differs from others, respect and

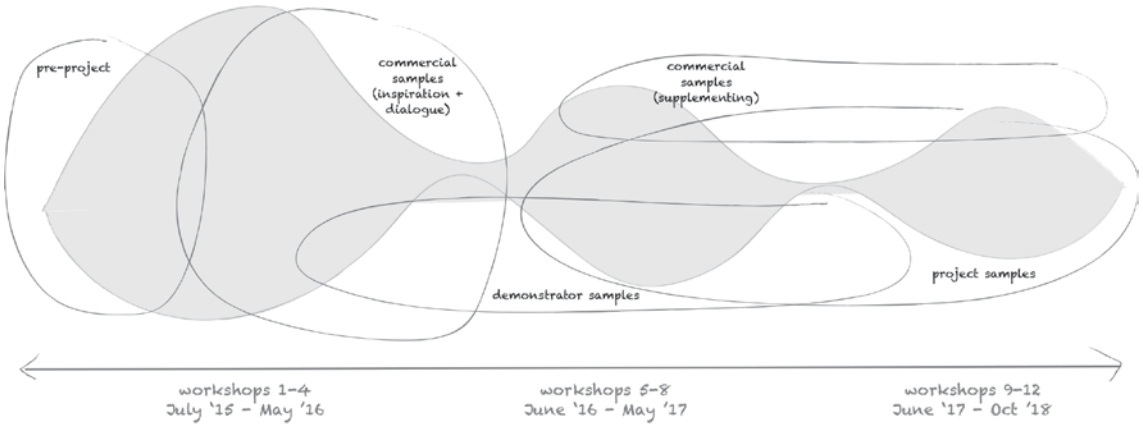

Figure 2.
Sketch of the four types of material sample mapped by primary use to a threephase diverge/converge design process diagram.

understanding of other peoples' ways of knowing follows. Pre-project samples therefore are valuable in the early phases of collaboration to help participants to start to understand the varied viewpoints of their partners (Gilley et al 2010).

Although they were used intermittently during the first five workshops, pre-project samples were largely superseded by the introduction of commercial samples in workshop 2, moving the focus of the consortium on quite quickly from the technologies now, to what the technologies might do in the project's future, their potential. The pre-project samples therefore had a fairly brief role at the beginning of the project, but their use was important not only for showing what was already known and possible – the know -what and -why (Jensen 2007), but for allowing participants to start to frame the questions that would allow them to understand the differences between themselves and the other collaborators, and developing the 'know-who' dimension of the collaboration.

Commercial samples

In workshop 2 participants were asked to bring "material samples that you find interesting" (figure 3) with the aim of exploring in group-discussions "where it is possible in the tech-process have some intervention and 'change' occur; and how these affect the final fibres/materials" (Workshop 2 Agenda). The intended outcome was a

map of co-created materials characteristics that would be ‘interesting’ for the new fibres as shown in figure 3. The resulting abundance of mainly commercial samples formed the basis of the reference collection for the whole project.

Figure 3.
Workshop 2: Commercial samples brought by participants and the co-designed set of material characteristics resulting from the discussion.

The samples clearly stimulated discussion, but there appeared to be more difficulty for non-experts to understand the differences between textile samples (beyond the fibre type). There was also a lack of available data for some of the samples, meaning that experts were less able to understand how those characteristics were technically achieved, which presents a significant barrier to cross-disciplinary communication and resolving the translation between tacit and codified language.

However, commercial samples were useful for beginning to learn to communicate and build a project language around the material technologies (Hornbuckle 2018). The dominant role of these samples at this stage, was in one-2-one and open discussions. For example, in one open discussion during workshop 3 a textile designer wanted to know whether a silk-like polyester could be achieved. A textile

engineer was able to provide a range of ’dtex’ for a silk polyester and then the fibre scientist was able to locate a sample made within the ‘dtex range’ of the fibre produced in the project. Commercial samples – indeed, materials collections or libraries of any sort - are particularly useful for this stage because they can demonstrate great variety of material characteristics which opens up discussion and offers more potential for providing the desired reference point at the appropriate time (Akin & Pedgley 2016).

The role of commercial samples changed in the second and third phases of the project, when they were used to fill in gaps in the material supply chain. Commercial materials were instrumental in enabling the manufacturers and designers to work up full product prototypes which could communicate the potential of the materials to wider audiences.

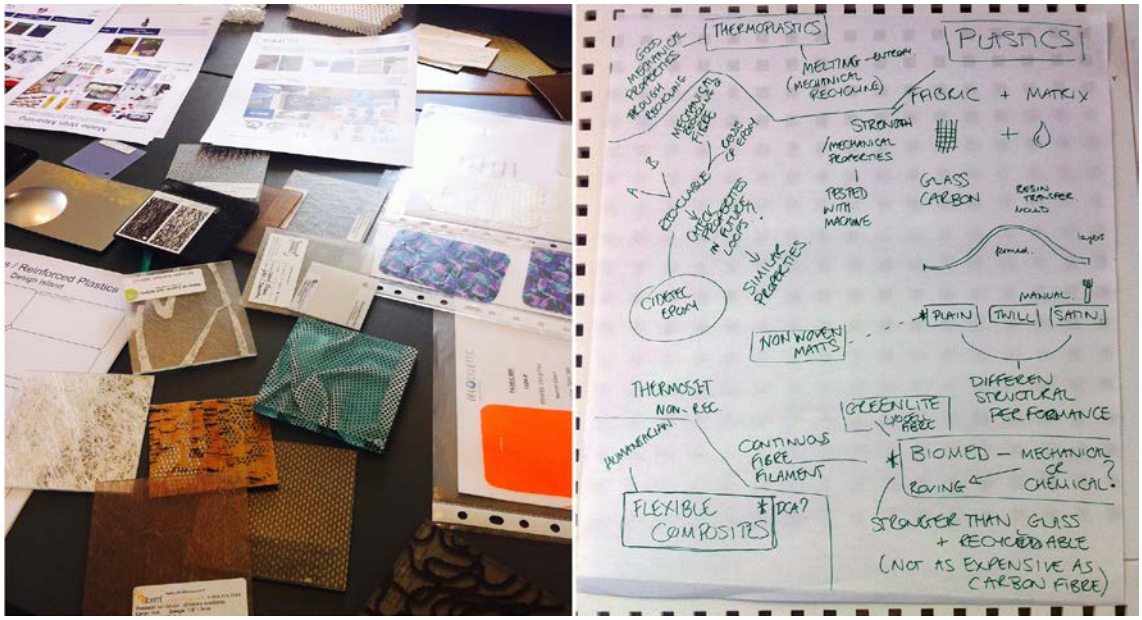

Figure 4.
Workshop 5: Demonstrator samples made by composite engineers and the resulting discussion captured within the workshop.

Demonstrator samples

Samples created within the project – but not as a direct response to a design request – are able to demonstrate some potential for development which is unique to the partners operating as part of the project consortium, therefore these samples uniquely embody information and knowledge about what is possible within the project limitations. As with the pre-project samples, they also have more complete and more accurate data to describe their making. Demonstrator samples of this kind first appeared in workshop 2, where the composite engineers had obtained some materials from the textile manufacturer to demonstrate the potential of different textiles when encapsulated within their resin. However, it wasn't until workshop 5 that their value became apparent. With a more specific focus on composites, the engineers used the composite demonstrator samples to lead discussions about their process, and the potential of their technology when combined with the fibre technologies for design applications. This session in particular created a lot of interest and discussion which was noted by one of the facilitators:

> Especially these composite things, [participants] could get, like, better understanding what kind of possibilities we have in the project to combine the textile and plastic. […] I could say that they helped them to go forward with this, the design concepts and get some technological understanding about those limitations.

The significance of the sampling strategy implicit in demonstrator samples, is that it connects the knowledge of one partner to another within a tangible artefact, making that connection and its potential value to various partner tasks, visible, concrete and available (Jensen et al 2007; Sandin & Stappers 2014). Although the composite demonstrator samples didn't contain any material produced by the novel technologies (as these were slower to produce sufficient material for samples), they were able to

Figure 5.
Workshop 9: Project samples presented by manufacturers and designers related to specification sheets, linking all design and material information.
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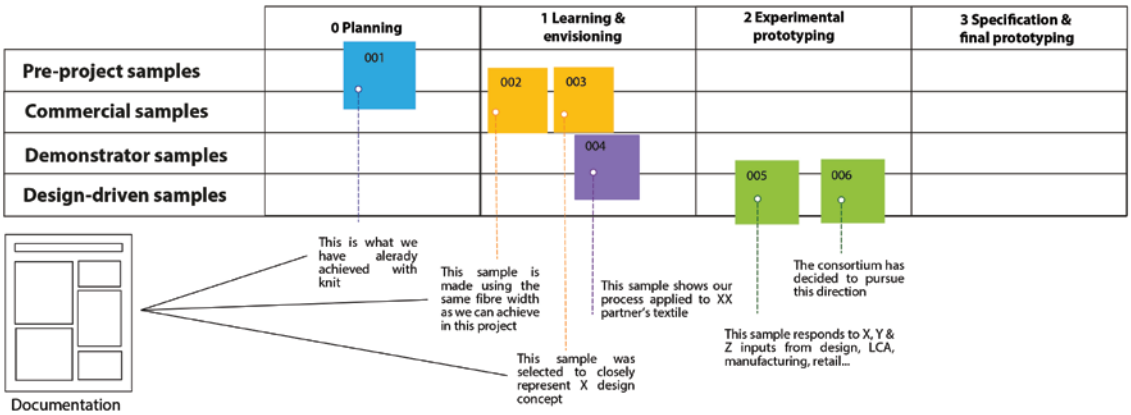

Figure 6.
Systematization and documentation of key samples from the outset could have helped to build a narrative for the collaboration and maintain momentum.

demonstrate the potential of the material within the project to designers and other partners by connecting expertise. This observation supports the finding of Barati & Karana (2019) suggesting that making demonstrator samples could have been a strategic part of the knowledge sharing between different partners from the outset of the project. Demonstrator samples therefore could be instrumental in developing the 'know-who' form of knowledge (Jensen et al 2007), as part of a strategic approach to collaborative making from the outset of the project, as suggested by one interviewee:

> If you want to have a methodology, like what is described in Trash 2 Cash implementation, you need to have materials … first months you need to start to work with [project] materials. [TechMLO-2]

Project samples

From workshop 6 onwards the focus shifted as materials R&D began to produce samples in response to design concepts. These were termed 'design requests', informed by expertise from around the material lifecycle as described by Goldsworthy & Ellams (2019). Within the textile stream, the material potential continued to be more challenging to communicate through the making of samples; the novelty added through subtle finishes and yarn widths demonstrated very little difference in handle or look. As the workshops progressed however, and project samples became more refined, they embodied more and more of the expertise of the consortium. As Niinimakki (2018) observes this was not a straightforward process, it was 'messy', and the fibre scientists in particular found it frustrating that the faster pace of material and design development downstream of their technology meant that the limitations of their process were not understood or respected, as one scientist explains:

> Sometimes it was very difficult to convince people that we could not do certain things, […] it was reoccurring, even though we addressed it, sometimes. It seemed like people forgot. [TechDSP-2]

The 'final' project samples, which were used to prototype garments and automotive parts for a public exhibition, were an embodiment of all of the expertise which contributed to the design and material development process. While the process had seemed unwieldly, confusing and frustrating, having a final 'thing' that embodied all of those contributions was hugely rewarding for everyone involved. Some of the final samples were made entirely out of the novel project materials while others used

combinations of commercial materials with processes and treatments developed within the project, applied to give the effect of the novel material.

Sample organization

There was no systematic organization of samples from the outset of the T2C project and the formation of a sample collection wasn't detailed as a task in the grant agreement with an assigned responsibility. The methodology team were motivated to incorporate samples as much as possible in the workshop activities and dialogue. However, in the early stages of the project samples were not adequately recorded with corresponding data for use at subsequent workshops, or indeed between workshops when partners may wish to refer to the topics discussed and the decisions made. The lack of a record and a selection process for materials samples based on the responses of participants in the workshop activities was seen by the lead materials facilitator as a shortcoming of the methodology plan:

> We need go ahead with other samples, you know, with [samples] that are able to transfer expectation or what someone has in mind, like a selection and step by step in which you can change your mind and so on. [DesMLO-1]

In a sense the materials samples themselves could have told a story of the consortium's thinking and decision-making which could have built collaborative understanding earlier on in the project. Instead, partners had to remember and recall those experiences individually without the tangibility of a common material sample narrative.

In workshop 6, as project samples were presented for the first time, they were linked to the processing data and also began to be linked to the corresponding design concepts using a complex coding system and spreadsheet. The information mainly served the manufacturing coordination and was fairly inaccessible for the rest of the

consortium. Gradually, the information relating to design concept and material samples was consolidated with other forms of knowledge into specification sheets.

As this was an experimental methodology it is perhaps not surprising that methods evolved as the need arose; not all challenges could be anticipated. However, this does raise the question of whether a more structured approach to recording discussions and decisions around materials samples from the outset of the project might have enabled more of an accumulative understanding of the material potential, and the knowledge and views of the different partners. The synthesis of all knowledge areas around specific design concepts and material samples towards the end of the project appeared to cement understanding between partners, enabling them to work more effectively together. Working practices are bound to be easier when the partnership is more mature, when design concepts are more refined and trust and cross-disciplinary language has formed; there are no guarantees that the approach described here would work better, however, the literature and practices common in material communication would suggest that a strategic organization of samples and related information could be beneficial as illustrated in figure x. In this way each sample becomes a vehicle for knowledge exchange and learning towards mutual understanding which helps to move developments forward in a constructive and productive direction.

The role of materials samples in multidisciplinary collaboration: towards a general framework

The case study research reveals that materials samples have complex roles within a multidisciplinary collaborative materials development project. Some of these roles are consistent with those reported by others, for example acting as a reference point during dialogue and to learn one another's language (Wilkes et al 2015; Ashby & Johnson

2002), and as inspiration for design (Akin & Pedgley 2016), helping designers to

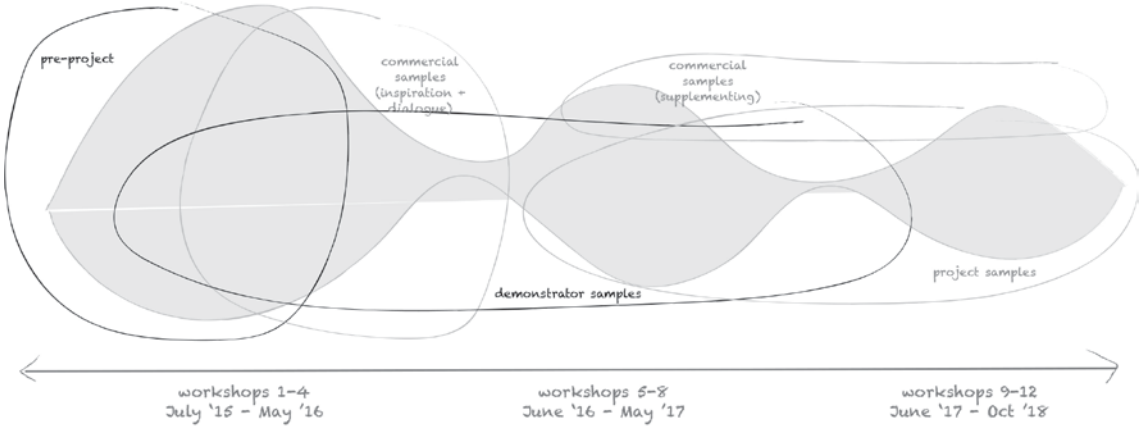

Figure 7.
Revisiting Figure 2, the sketch shows how pre-project and demonstrator samples could have a greater role at the beginning of the collaboration.

understand material potential and affordances (Karana et al 2010). However, when framed within a co-design workshop setting, it becomes clear that materials samples also mobilise different forms of knowledge making them available to a range of participants, not only to designers. Materials samples embody scientific knowledge – the 'know-why' and 'know-what' – but also knowledge about the collaboration and the roles of other participants within the group – the 'know-who'. Pre-project samples are important very early in the collaboration as the first specific reference samples, which provoke participants to think about how their lens is different from others' and therefore begin the process of building respect and trust between collaborators. Demonstrator samples, if made early in the collaboration, can speed-up understanding of who can do what in the material-making-chain, and therefore enable people to better understand the materials potential and the way forward. Materials samples also embody 'know-how', especially when demonstrating making processes, or when materials-led designers use experimental practices such as making and playing to explore novel materials (Barati & Karana 2019; Wilkes et al 2015). For this reason, one of the recommendations resulting

from this study is that more attention in paid to the role of pre-project samples and demonstrator samples in building on the ‘know-who’ and ‘know-how’ learning opportunities from the outset of the project as illustrated in figure 7. Although hands-on ‘making together’ co-design practices were not observed in T2C as this was not seen as practical within the project limitations, previous authors have argued for this to be given priority in design and materials development projects where creative applications of materials is a central aim (Barati & Karana 2019; Hornbuckle 2018). These hands-on methods can be considered as part of the making of demonstrator samples within this framework (Hornbuckle 2018; Wilkes et al 2015). Commercial samples are understood to be a source of inspiration for design and as boundary objects for supporting cross-disciplinary dialogue. However, they have an additional role within the co-design of materials, particularly those involving complex material-making-chains, as a source of supplementary material if gaps open up in the material-making-chain.

From this research a general framework can be proposed as illustrated in figure 8. Jensen (2007) warns against making the forms of knowledge absolute in any given context, so these are intentionally not fixed to one or other type of sample, but they sit between the sample types they are most closely relate to. All of the samples contribute towards the central goal of the co-designed project samples.

The framework is contingent on a system of organization and framing which documents information relating to the samples from the outset of the collaboration. The framework also refers to the practical but important role of a materials sampling strategy that supports the material-making-chain so that lapses in material availability are not detrimental to the project progression, which caused frustration and tensions in the case project.

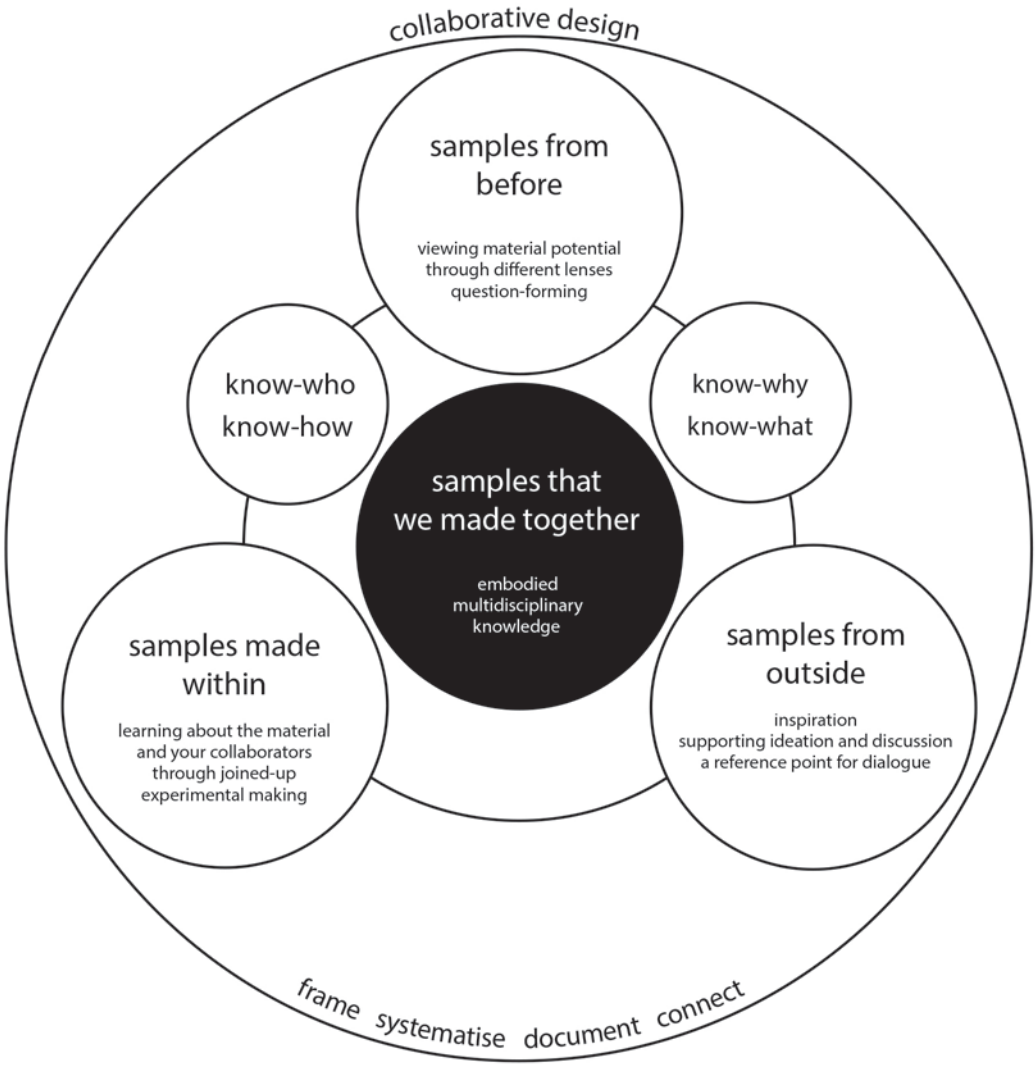

Figure 8.
Mobilizing Materials Knowledge: A general framework for strategic use of material samples in collaborative design and materials development.

While the flow of project samples was expected to come through the material-making-chain from the scientists to the manufacturers and then to the designers, this is far from the ‘messy’ and iterative nature of the sampling observed in the case. Although a high demand was placed on the scientists to produce samples at an unprecedented quality and quantity, there was a great deal of effort further downstream to experiment, to plug the gaps, and to respond to the requests made through the co-design activities. Demonstrator and commercial samples were also provided by designers to scientists and manufacturers, therefore the flow of samples was not unidirectional; indeed, the four

sample types came together from multiple sources, representing many of the disciplines represented in the project, to complete a puzzle of material understanding for the whole consortium.

This study has necessarily held a narrow focus on materials samples and therefore doesn't take into direct consideration all of the tools, methods and processes that were used in the case to support the design-driven methodology. This work also assumes design collaborations which seek a systemic approach to circular design and materials as well as other complex problems, will increasingly involve a large number of participants and therefore the challenges which this framework seeks to address will be relevant. However, it is hoped that the thinking behind this framework could be useful for a range of multi-disciplinary collaborative projects involving the development of artefacts, by building understanding around the potential role of material things corresponding to the four sample types explored here, 'those from before', 'those that are made within', 'those from outside', and 'those that we made together', and the actions and types of knowledge that they mobilise within the collaboration: supporting 'know-who', as well as dialogue and inspiration.

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