R&D MANAGEMENT

The microfoundations of mission-led interdisciplinary collaborations: The role of design principles

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Mission-oriented (MO) research aims to address social, economic and policy goals through an agreed and evidence-based set of 'missions'. Vital to achieving a mission are bottom-up and cross-organisational interdisciplinary collaborations. However, these collaborations are often time and resource intensive. Paying attention to microfoundation behaviours can elucidate the individual capabilities required for mission-oriented science. Design-driven approaches have proven useful in supporting the microfoundations of interdisciplinary collaborations. However, we know little about what design principles support MO research. To understand this, we conducted a workshop built on a Concept-Knowledge (C-K) design principles as part of a longitudinal study of a mission-oriented interdisciplinary science innovation programme in New Zealand. Our results indicated that the C-K principles of knowledge mapping, concept exploration and mindful deviation enhanced workshop participants' willingness to creatively experiment across disciplines, provided a shared research directionality and addressed many of the barriers identified in the longitudinal study. We argue that our findings complement and deepen empirically driven microfoundational research by unpacking the specific role of design principles in inducing the behaviours that are essential to advancing large-scale mission-oriented research collaborations.

1. Introduction

Mission-oriented (MO) research – large-scale cross-organisational collaborations to address grand social challenges – is increasingly seen as a way to advance new knowledge to address societal challenges (Ministry for Business and Employment, 2015; Mazzucato, 2018). Such challenges require collaboration across disciplines, sectors and participants organisations (Schmickl and Kieser, 2008; Van Rijnsoever and Hessels, 2011) given that innovative research is "more extensive and powerful than [the] constituent parts" (Rhoten and Pfirman, 2007, p. 58). In turn, individual collaborative capabilities and motivations need to be in place to create innovative solutions to achieve a given mission (Ulnicane, 2016; Compagnucci and Spigarelli, 2020).

Prior research has investigated inter-organisational collaborations to drive innovative MO research (Freeman et al., 2019; Compagnucci and Spigarelli, 2020). Our interest is on microfoundations that examines how macro-outcomes, such as those associated with grand societal challenges, emerge from bottom-up cross-organisational interdisciplinary interactions (Foss and Linder, 2019; Mazzucato, 2019, 2021). Such research assesses individuals' motivational and cognitive performance in explaining organisational outcomes and has arisen as a "reaction to an over-emphasis on collective constructs, as well as the seeming disregard for individual-level and social interactional considerations in explaining organisational outcomes" (Felin et al., 2015, p. 582). In other words, paying attention to microfoundations can elucidate the linkages amongst individual behaviours and capabilities, the organisations in which individuals operate – including temporary or time-limited cross-organisational settings brought together for MO research – and the broader systems within which they operate (Scuotto et al., 2022).

Microfoundational capabilities are crucial for interdisciplinary collaborations, and there have been calls for more research on how such capabilities can be facilitated in these contexts (Alves et al., 2004; Cummings and Kiesler, 2008; Toker and Gray, 2008; Plattner et al., 2010; Hamann et al., 2016). This is precisely the focus of this study, and in particular the principles that can help aggregate individual disciplinary and other knowledge to enable new cross-organisational collaborations to address a mission.

Design tools and practices facilitate collaboration by accounting for and then devising approaches to address the barriers to and enablers of innovation in interdisciplinary and cross-organisational teams. Such facilitation is necessary as MO challenges are large-scale 'wicked' problems (Churchman, 1967; Crowley and Head, 2017) that require trust and communication amongst individuals and their organisations to build cooperation, flatten hierarchies and improve team dynamics (Chamberlain and Partridge, 2017; Blomkamp, 2018; Heiss and Kokshagina, 2021; Kokshagina, 2022). Central to this is the need to select the most effective tools that facilitate innovative exploration across disciplines.

While there are many design-driven approaches (e.g., design thinking, co-design) that aim to solve problems in different contexts, anticipate new perspectives or integrate knowledge from different disciplines (Le Masson et al., 2017; Magistretti et al., 2021), for the purposes of this study we have selected the Concept-Knowledge (hereafter C-K) design approach. As a human-centred design approach, C-K enables microfoundational skills and behaviours to address the MO research premises of bottom-up creativity, experimentation, and shared directionality (Mazzucato, 2018, 2021) through a set of design activities (Hooge et al., 2016; Hatchuel et al., 2018). While there are commonalities with other design theories and methods, C-K relies on a set of specific principles and "a coherent set of normative ideas and propositions, grounded in research, which serve to design and construct detailed solutions" (Van Burg et al., 2008, p. 116). Such principles include: mapping the knowledge base of an interdisciplinary community (hereafter, knowledge mapping); finding non-conventional ways of addressing a problem (concept exploration); and stepping away from established disciplinary structures to reframe how to approach a problem (mindful deviation) (Hatchuel et al., 2004; Luo, 2015; Chen et al., 2017; Vourc'h et al., 2018; Plantec et al., 2019).

This study explores the microfoundations of a MO research collaboration and sheds light on how design principles may be used as a tool to encourage MO collaborations. The question that guides our approach is:

How do C-K design principles support the microfoundations of MO interdisciplinary collaborations?

To address our research question, we begin by exploring the background of mission-oriented science. This is followed by a brief overview of the microfoundations of interdisciplinary collaboration and how C-K design principles address interdisciplinary collaborations, acting as a potential approach to MO research. We then present our research methodology, discussion and contribution.

2. Literature review and theoretical framing

2.1. *The background of mission-oriented science*

Mission-oriented research refers to a systemic approach to solving societal issues through coordinating collaborations across different disciplines, stakeholders, and sectors. It aims to address wider social, economic and policy goals through an agreed and evidence-based set of 'missions'. MO research seeks to promote the development of critical technology capabilities for addressing grand challenges, such as climate change (Ulnicane, 2016). It is centred on two main assumptions. The first argues that social, economic and environmental conundrums may be tackled by creative processes rather than changes in behaviour or large regulatory activities. The second assumption recognises academic creativity and collaboration trigger broader innovation processes (Mazzucato, 2018).

A mission seeks to bring about change and establish a system to manage innovative endeavours. It entails impacting and encouraging significant transformations to break old dependencies. A mission divides large, difficult problems into smaller chunks through collaborations requiring leadership, vision, and purpose (Mazzucato, 2018). However, vision and purpose cannot be imposed; they result from genuine interaction with society, science and government (Mazzucato, 2021). Mazzucato describes the Apollo programme as the century's riskiest public-sector endeavour, based on experimentation, and partnerships between government, research organisations and businesses. In this sense, MO research embeds collaborations across sectors and disciplines, involves risk and bottom-up experiments and relies on continuing feedback loops and serendipity (Rodrik, 2004; Mazzucato, 2018, 2021). Creating critical technology and innovation for mission-oriented goals require interdisciplinary collaboration amongst research institutions, government and industry partners (Gibbons, 1994; Kostoff et al., 2004; Schmickl and Kieser, 2008; Hacklin and Wallin, 2013; Hamann et al., 2016); creative processes (Mazzucato, 2018); bottom-up solutions and experimentations; and shared sense of directionality (Mazzucato, 2021).

Individuals' motives and social interactions are essential for these complex initiatives (O'Kane et al., 2019). However, understanding how this works in practice has received scant attention. Paying attention to microfoundations can help to clarify the connections between individual behaviours and capacities, organisations, and larger systems (Scuotto et al., 2022).

2.2. *Microfoundations of interdisciplinary collaboration*

Microfoundational perspectives account for individual experiences and behavioural dynamics in organisational settings and examines how individual attitudes, behaviours and inter-relationships contribute to broader organisational outcomes (Felin et al., 2015; Sousa-Zomer *et al*., 2020; Scuotto et al., 2022). The literature indicates that individual-level attributes and experiences are more predictive of academic entrepreneurship than social environments (Clarysse et al., 2011), with innovative capabilities resulting from the interplay between individuals and organisational and managerial structures, systems, processes, and procedures (Schneckenberg et al., 2015). Hence, attention to microfoundations can pinpoint the enablers and barriers to innovation collaborations (Locatelli et al., 2021).

Albats et al. (2020) list characteristics such as eco-centrism or extroversion as vital for shaping microfoundations of strategic partnerships. More broadly, the behavioural responses of entrepreneurial-university 'agents' can play a critical role in shaping innovation ecosystems (Johnson et al., 2022).

According to Scuotto et al. (2020), technology transfer is enabled by the microfoundational processes of intention formation; individual motivations, such as mutual interpersonal trust and perceived benefits; and self-efficacy for sharing knowledge. Aversa et al. (2021) find that team formation and cluster genesis can be generated through emotional microfoundations such as localising passion to create shared emotional energy, and a shift of purpose, to create a new shared domain. Shared emotional energy was also identified (Elliot, 2006; Gable, 2006), as a driving force to positive attitudes to social and collaborative research bonds. In addition to that, individuals' motivations builds empathy, which can be a catalyst for collaboration in innovation processes (Price et al., 2015). In this sense, Lam and Lambermont-Ford (2010) posit the importance of addressing researchers' motivation in an initial phase of collaboration to help to overcome barriers to collaboration.

Multiple barriers affect interdisciplinary and cross-organisational research. Differences in disciplinary norms, culture and language across individuals and organisations impede insight and creativity

(Jansson and Smith, 1991; Hadorn et al., 2008; Crilly, 2015; Sio et al., 2015) and require individuals to develop a shared lexicon to improve communication and intelligibility (Carlile, 2004; Hsiao et al., 2012; Corsaro, 2018). Even with a shared lexicon, researchers have to negotiate diverse interests to develop mission-oriented innovation (Hsiao et al., 2012).

To overcome these challenges, interdisciplinary teams devote considerable time negotiating agenda and procedures to build connections and trust (Alves et al., 2004; Cummings and Kiesler, 2008; Toker and Gray, 2008; Plattner et al., 2010; Hamann et al., 2016). The additional workload and time that researchers must put into interdisciplinary co-operation can be a factor in decreasing motivation to foster collaborative relationships (Alves et al., 2004; Cummings and Kiesler, 2008; Toker and Gray, 2008; Hamann et al., 2016).

Various strategies have been proposed to overcome these barriers. These included reflexivity (Crilly, 2015); designing the phases of research in a recurrent order, whereby the sequence of research stages in interdisciplinary research differs from traditional problem-solving research and is determined by the type of problem under enquiry (Hadorn et al., 2008); adopting a boundary-spanning framework approach based on principles of transferring, translating and transforming knowledge (Carlile, 2004); and making use of boundary objects for knowledge sharing (Corsaro, 2018).

Design approaches such as C-K, road-mapping (Kostoff and Schaller, 2001; Phaal et al., 2001, 2007), design thinking (Borges and McNamee, 2022) and co-design methodologies (Farr, 2018) have also been used to support interdisciplinary collaboration settings. Despite increasing use of design tools and processes in facilitating interdisciplinary collaboration settings, how design principles can help shape the microfoundations of MO research projects remains unclear. Because the C-K design approach pays attention to how individuals in interdisciplinary collaborations are empowered or restrained by their situational or organisational context, in this study, we explore whether C-K principles support microfoundations of MO interdisciplinary collaborations.

2.3. *Design principles for interdisciplinary collaborations*

Design research has identified tools, approaches, models and procedures to address the challenges of interdisciplinarity (Masson et al., 2017) while creatively intervening to devise innovation solutions (Schmidt and van der Sijde, 2022). Accordingly, design processes and/or methodologies aim to support knowledge exchange across disciplinary boundaries by enabling individuals to think through problems in a generative way to arrive at potential solutions (Steen et al., 2011; Dalsgaard, 2017; Broadley and Smith, 2018; Inie and Dalsgaard, 2020; Peters et al., 2020; Heiss and Kokshagina, 2021; Schmidt and van der Sijde, 2022).

Many design approaches referred to in the literature have common design principles. These include principles of concept generation, concept originality, concept variety, and exploration value (Vourc'h et al., 2018); ideation, knowledge mapping, transfer and transformation, and creating a common language (Chen et al., 2017); overcoming fixated reasoning and de-fixation processes (Plantec et al., 2019); and explorative reasoning (Garud et al., 2010; Agogué et al., 2012; Gill and Williams, 2014; Lenfle et al., 2016; Wrigley, 2017; Butler and Roberto, 2018). In this research we build on the C-K design approach. C-K explores individuals in interdisciplinary collaborations and their situational or organisational context. At the same time, individuals' activities create the microfoundations of institutional capacity to address a mission (Schmidt and van der Sijde, 2022). This understanding creates distinct requirements for interaction and collaboration, with C-K offering a structured methodology that acknowledges the interplay of micro-interdisciplinarity to address macro-oriented missions through the use of tools that encourage creativity, experimentation, and innovation directionality (Agogué et al., 2012; Agogué and Kazakçi, 2014; Schmidt and van der Sijde, 2022).

A structured design approach can help opening closed systems (Guertler et al., 2020), thereby helping participants break through self-reinforcing prior knowledge. C-K methodology is also structured around bottom-up solutions and experimentations, potentially enhancing the microfoundational aspects of MO research collaboration (Gibbons, 1994; Kostoff et al., 2004; Schmickl and Kieser, 2008; Hacklin and Wallin, 2013; Hamann et al., 2016; Mazzucato, 2018, 2021).

To enhance interdisciplinary collaboration, such as expanding participants' knowledge of an unknown disciplinary field and to overcome some of the barriers identified in the literature, for instance knowledge fixation (Hatchuel et al., 2004; Luo, 2015; Chen et al., 2017; Vourc'h et al., 2018; Plantec et al., 2019), C-K observes three broad design principles:

- Mapping the knowledge base of an interdisciplinary community, which includes concept variety, knowledge transfer, mapping and creating a common language (knowledge mapping);
- Finding non-conventional ways of addressing a problem, which includes ideation, concept generation, concept originality, knowledge transformation, explorative reasoning (concept exploration);
- Stepping away from established disciplinary structures to reframe how to approach a problem including overcoming fixated reasoning and defixation processes (mindful deviation).

Knowledge mapping involves unveiling or mapping the knowledge base of an interdisciplinary community and revealing hybrid scientific and technical knowledge (Agogué et al., 2012) to bridge disciplines and actors (Wrigley, 2017). The mapping incorporates concept exploration of propositions based on imagination, creative chimaera, and 'lay' mental constructs to provide alternative pathways to address a problem (Agogué et al., 2012; Lenfle et al., 2016). Concept exploration also underpins the ideation process by finding *non-conventional ways* of addressing a problem (Butler and Roberto, 2018). Fixation, or "self-reinforcing knowledge", obstructs the creation of new knowledge (Agogué et al., 2012, p. 605). *Mindful deviation* refers to the process by which interdisciplinary teams or individuals consciously step away from established disciplinary or mental structures to reframe a particular way of thinking and approaching a problem (Gill and Williams, 2014). Mindful deviation refers to the capacity to dis-embed from established [mental] structures that define relevance in an innovation context, and mobilise a collective in the face of opposition and inertia (Garud et al., 2010).

We note that design for innovation research pays attention to individual-level processes and interactions (Sanders and Stappers, 2008; Blomkamp, 2018; Auernhammer, 2020). For instance, Hooge et al. (2016) explore how thanks to design-driven approaches, individuals engage in science innovation. What is less accounted for is how the underlying design principles shape the microfoundations of MO research projects.

3. Research methodology

Our study focuses on a mission-oriented New Zealand science innovation programme, Science for Technological Innovation (SfTI, 2018). SfTI, one of New Zealand's eleven National Science Challenges, was launched in 2016 with the mission of enhancing New Zealand's capacity to use physical sciences and engineering for economic growth and prosperity (MBIE, 2015). SfTI is organised into nine large research projects called Spearheads. SfTI Spearheads include an interdisciplinary array of social scientists, engineers, chemists, designers and physicists across 36 institutions comprised of universities, industry, Crown Institutes (government-funded research bodies) and Māori (the Indigenous people of New Zealand) with over 500 researchers funded. A social science team – Building New Zealand's Innovation Capacity (BNZIC) – has followed these projects to provide insights into the researchers' entrepreneurial skills and ability to connect and communicate research to industry and Māori.

The study analysed here was as a response to observations generated in the first phase of grounded and exploratory research (see Table 1) that focused on the enablers and barriers to MO research innovation.

3.1. Phase 1. Longitudinal study

In Phase 1, BNZIC collected data through multi-method, longitudinal research, primarily through grounded and inductive methods (Woodfield et al., 2021), to explore the complexity of SfTI's collaborations as they evolved. We captured primary data from observations and recordings of the teams' meetings, *in situ* and online, and 87 group and individual semi-structured and open-ended interviews ranging from 20 to 50 min (see Table 1). We also drew on reports as secondary data (Braun and Clarke, 2006; Fereday and Muir-Cochrane, 2006; Carter et al., 2014).

We used NVivo with an inductive approach (Eisenhardt et al., 2016) to organise and code the data to reveal overlapping themes (Aronson, 1995; Braun and Clarke, 2006; Fereday and Muir-Cochrane, 2006). Our analysis identified broad patterns of participants' experiences and ideas to form a picture of the collective collaboration experience (Aronson, 1995; Braun and Clarke, 2006). We then clustered these into four thematic barriers to cross-organisational inter-disciplinary collaboration.

Table 2 summarises the four 'barrier' clusters and suggested that, in some cases, processes to form collaborative teams may not have been designed or structured sufficiently to overcome individual researchers' disinclination to collaborate. This analysis confirmed our generic observation that some of the SfTI spearheads quickly cohered into

Table 1. Research phases

Research phase	Methodology	Data	Analysis	Duration
Phase 1: Research across spearheads	Grounded and inductive	• 87 open and semi-structured interviews; • Workshop observations; • 3 Meeting notes; • 5 Spearhead reports	Thematic	Longitudinal (3–4 years)
Phase 2: C-K workshop	Structured design-led	• 14 hr of audio-recording of the workshop (including group discussions); • 152 photos of the interactions between participants; • BNZIC observation notes; • 22 photo-task responses	• Thematic; • Photo-task	• Four and a half hours (workshop); • 20 min to a week for the completion of the photo-task activities

Table 2. Cross-organisational interdisciplinary barriers to collaboration

Themes	Barriers	No. data points	Exemplifying quote
Collaboration barriers	• Disciplinary silos • Lack of a common language • Knowledge misalignment • Self-reinforcing prior knowledge • Miscommunication	20	"My viewpoint was completely different from his viewpoint, and then when we integrated the two, we were actually talking about the same goal, but the way we look at it is different. So the end product is the same, but he sees what the opportunity is – I see where the science challenge is?"
Barriers to team formation	• Lack of clarity of team roles • Unclear team objectives • Others' expectations of individuals • Lack of alignment of individuals' technical knowledge	11	"I think a lot of collaborations are … set up this way as well, where it's a loosely-defined collection of projects, and everyone's really just doing their own thing, and getting together occasionally to share the results"
Time barriers	• Non-project time constraints • Time taken to align expectations • Amount of time to test science hypotheses/models etc • Time taken to build relationships	14	"[The team] basically spent two-plus years just figuring out – in the program I'm – figuring out what we're going to do … In the end I just got to a point where I said, this is the thing I think will fit really what things we want to do … It's not necessarily the most expansive thing; it's something we can deliver in the timeframe"

Technical science barriers	• Technical uncertainties
	Lack of:
	  • Access to technical knowledge
	  • Depth of research problem
	  • Expertise in how to approach the problem
	  • Complexity of the research problem
		17	"So, it framed up as this personalised value chain, and just on reflection I think we just got it too narrow at that point"

active interdisciplinary teams with defined research objectives, while others took 18 months. In other cases, researchers failed to form a coherent interdisciplinary research proposal to meet the funder's expectations of innovative science in the allocated time. This was despite considerable time invested through workshops, the involvement of external facilitators and advisory meetings with the funders. In some cases, these teams decided to stop after a few months or, in one case, two years. Similar findings were found by Clement and Puranam (2018), who noted that an unstructured approach to

Table 3. Workshop participants

Spearhead	No. of participants	Discipline	Codenames
Additive manufacturing	21	• Bio-material scientists • Engineers • Product designers	P1 to P21
Robotics	12	• Engineers • Computer scientists • Manager	P22 to P32

Table 4. Workshop activities and design principles

Workshop sections	Activity	Design principles
1	• Participants from two spearheads join groups according to their areas of interest. • Participants map out their disciplinary knowledge by sketching their current research area, respective methods, and approaches for result sharing. • Participants identify promising areas for further research in sub-groups. • In sub-groups, participants makes use of negation, inversion or abstraction, to propose alternatives to their initial concepts (See C-K canvas, Figure 1). • Participants share their mapping activity with their main group.	• Knowledge mapping • Concept exploration
2	• Participants share with the whole group their group's promising areas for furthering research, including respective barriers and enablers. • The whole group provides feedback and alternatives to the proposed barriers.	• Knowledge mapping • Mindful deviation • Concept exploration
3	• Based on the whole group discussion, participants are asked to identify, as a group, the ideas that they would like to develop further. • Participants are asked to imagine the most disruptive concept for both additive manufacturing and robotics for each idea.	• Concept exploration
4	• Based on the feedback received by the whole group, each group elaborates on the most ambitious idea and pitch it to the whole group. • The whole group votes for the best disruptive idea.	• Mindful deviation • Concept exploration

organisational management might lead to a decline in interactions.

Based on these findings, the BNZIC team decided to implement a C-K designed workshop to explore how the barriers might be addressed between two research teams largely new to each other.

3.2. *Phase 2. C-K workshop design and research methodology*

A facilitator versed in the C-K approach led a four-hour workshop. The workshop was designed for two different SfTI science teams, one focused on additive manufacturing and the other on robotics (Table 3). The additive manufacturing team was formed in 2016 to develop bio-based products and materials for 3D/4D printing. The robotics team focused on robotics for rugged environments started afterwards, in mid-2017. All participants were informed of the workshop's purpose, and a University ethics application was sought prior.

The workshop consisted of four activities, each exploring a particular and sometimes overlapping design principle (Table 4).

Data collected from the workshop consisted of audio recordings, photos of the participants' interactions and notes from the observers. In addition to the recordings, there was also a photo-task activity. Photo-task enables reflection on a specific phenomenon by capturing a self-selected visual image (Wang and Burris, 1997). Such an approach positions participants as actively involved in the data collection, encouraging a deeper reflection upon the image and the individual's experiences, thereby bringing to the surface microfoundational processes not readily articulated verbally. In this study, the photo-task activity involved participants emailing a photograph and description that summarised their experiences and impressions of the workshop (see Table 5).

A team of four social researchers collected extensive observational data from the workshop. In participant observation, the researcher is immersed in the subject of study and becomes the research instrument (Brannan and Oultram, 2012). Participant observation helps investigate how individuals see the world (Silverman, 2006), and produce significant insights when triangulating the observation data with other primary and secondary data (Lofland et al., 2006).

Participant observation data comprised the researchers' field notes during and after the workshop. These notes recorded subgroups and whole-group actions and interactions as well as reflections on what happened during the workshop. The participant observation and the field notes from the four observers allowed a variety of views of the workshop and gave context to the photos-analysis.

Table 5. Summary of workshop findings

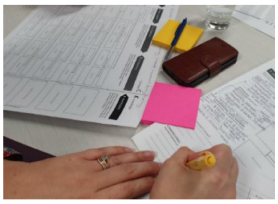
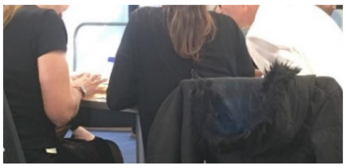
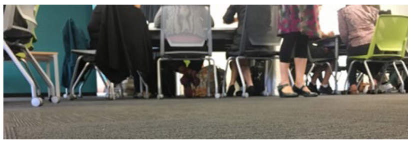
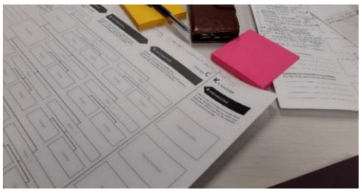
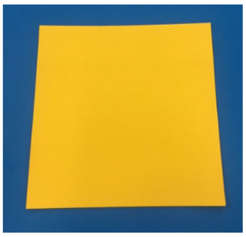
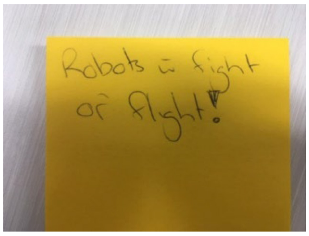
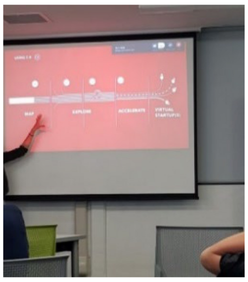
C-K principles	Photo-task (PT)	Related quote	Codename	Addressed barriers
Knowledge mapping		Team collaboration. Alone you go fast but together we go further!	PT1	Interdisciplinary collaboration; time
Knowledge mapping		I selected [this picture] cos it shows the process in which members all joined in discussion and each one contributed some ideas he/she came up with	PT8	Interdisciplinary collaboration; technical science; time
Knowledge mapping; concept exploration		The team enjoys refining the words that crystallise our chosen concept. The enthusiasm, passion and humour within the room made the afternoon a pleasure. This photo captured the mood for me	PT3	Interdisciplinary collaboration; time
Knowledge mapping; concept exploration		Robotic and 4D printing scientists at work	PT13	Interdisciplinary collaboration; technical science
Concept exploration		A great method to get thinking together and enabling surprising insights. An interesting approach for collaborative actions that can create 'high-fliers' and 'moonshots', but still requests from scientists to stay with both feet on the ground of the real-world thingies	PT23	Interdisciplinary collaboration; technical science; time

Table 5. (Continued)

C-K principles	Photo-task (PT)	Related quote	Codename	Addressed barriers
Concept exploration		Make sure the object is specific enough [referring to the facilitator's approach]! Image shows our team on our second attempt. We probably would have had a third attempt if time had allowed	PT2	Technical science
Concept exploration		The day started as a blank post-it … but progressed to a whole lot of great ideas	PT28	Interdisciplinary collaboration; technical science
Concept exploration		Some light amidst the depths …	PT30	Technical science
Concept exploration; mindful deviation		Captures the breadth of the exploration and the fun of the concepts	PT4	Technical science
Mindful deviation		Learning to think differently for more creative ideas	PT26	Technical science
Concept exploration; mindful deviation		I was an empty vessel hoping to be filled …	PT25	Team formation; technical science

(Continues)

Table 5. (Continued)

C-K principles	Photo-task (PT)	Related quote	Codename	Addressed barriers
Knowledge mapping; concept exploration; mindful deviation		'Food for thought' Interesting possible process (food for thought) … In terms of collaborative project ideas, we have enough of a struggle to identify research ideas and collaborate effectively within our team within the fiscal constraint of spearhead that I think collaborating with another spearhead in new research ideas is too much of a stretch at the moment	PT22	Time

We also analysed 152 photos taken during the workshop and identified participants' body movements and postures to reveal unspoken emotions (Carney et al., 2005, 2010; Hall et al., 2005). The analysis focused on the performative, haptic and affective dimensions of participants' interactions, allowing a deepened analysis of the power relations inherent in collaborations that involve heterogeneous participants from differing disciplines, examining how domination and resistance played out in the context depicted by the photo (Lorimer, 2010).

Our photo analysis required reflexive awareness of the cultural and political landscape inherent in bringing together participants from different institutions, attitudes, levels of seniority and interest, "paying attention both to the evocation of universals and the constant possibility of confusion, transgression or offence at an unfamiliar or unexpected response" (Lorimer, 2010, p. 245). As such, we were interested in understanding whether we could spot moments whereby old knowledge was discarded or un-fixed, and new knowledge was incorporated due to particular design activities deployed by the facilitator. To identify such moments, we drew on research on two universal nonverbal poses linked to participants' self-assurance, expansiveness (i.e. taking up more space or less space) and openness (i.e. keeping limbs open). In contrast, a closed-limb position is identified as the subject having lower self-assurance (Carney et al., 2005, 2010; Hall et al., 2005). The photo-task encouraged participants to promote deep and critical reflections on how they experienced the workshop (Wang and Burris, 1997), thereby bringing forth the unconscious micro-level processes not readily articulated verbally.

In order to triangulate the data from the workshop, we coded the audio data and analysed it thematically (Braun and Clarke, 2006; Fereday and Muir-Cochrane, 2006) to explore how the barriers were addressed by the design-led principles. These codes were then triangulated against the photographs and photo-task activities (Schwartz, 1996; Rose, 2008). Finally, we assessed the reactions to the workshop against the key themes from the broader barriers identified in the longitudinal study to see to what extent the workshop addressed one or more of these.

4. Findings: design principles and barriers to interdisciplinary collaboration

The following outlines how design principles were applied and perceived, bearing in mind that the workshop was instigated to overcome the thematic barriers noted in Table 2: barriers to interdisciplinary collaboration, barriers to team formation, technical science barriers and time barriers. We present how each principle was deployed to deal with barriers.

Table 5 summarises the workshop findings, using key photos and quotations that correspond to design principles aimed at addressing the barriers identified in Phase 1 longitudinal study.

4.1. Knowledge mapping

The knowledge-mapping principle addressed collaboration barriers such as disciplinary silos or lack

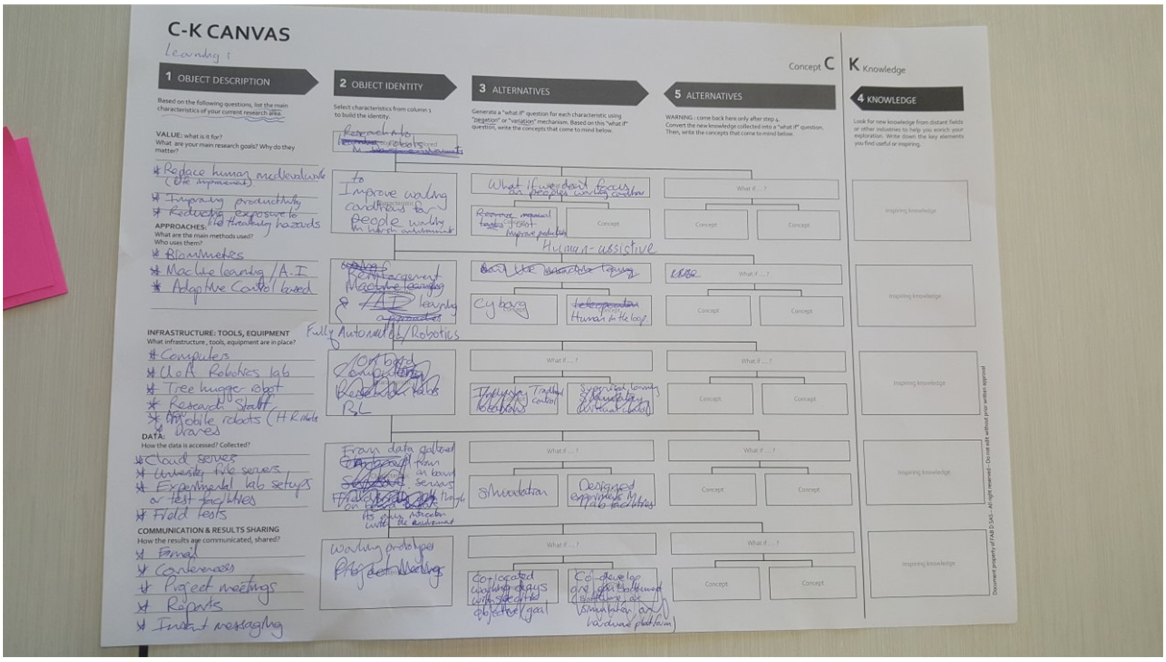


Figure 1. Workshop canvas template.

of a common language that emerged in the Phase 1 research. For example, comments such as "*everyone is really just doing their own thing, and getting together occasionally to share the results*" and "*we have to be very cautious and careful about making sure we understand each other's meanings*" were not uncommon in Phase 1. In contrast, as shown in the workshop canvas template (Figure 1), the participants undertook multiple iterations to clarify their responses to the knowledge mapping activity. In turn, this allowed them to negotiate and develop a shared language to align understanding across their respective disciplines. As Table 5 shows, knowledge mapping helped participants identify what disciplinary knowledge can be used to combine seemingly unrelated concepts. This was experienced with "passion", "enthusiasm", "humour", and "pleasure" (Photo-Tasks PT1, PT8, PT13, PT23, and PT28). With the help of the workshop canvas template (Figure 1), participants first had to describe their main research goals and importantly, why these goals mattered. Some participants stated that their research would "reduce exposure to life-threatening hazards" or "use renewable waste streams", while others noted that their motivation was "distributed manufacturing", "improved healing", and "personalised care for individuals".

The photo-task activities also revealed participants' willingness to collaborate, addressing barriers such as the large amount of time taken to build relationships for team collaboration. For example, expressions such as "*team collaboration. Alone you go fast, but together we go further!*", "*[…] the enthusiasm, passion and humour within the room made the afternoon a pleasure*", and "*A great method to get thinking together and enabling surprising insights*" revealed participants' positive attitudes towards social bonding in a short amount of time. In other words, knowledge mapping helped to overcome previously identified barriers of knowledge misalignment, miscommunication, disciplinary silos and inability to access technical knowledge.

4.2. Concept exploration

In the concept exploration phases, participants were asked to generate 'what if' questions to help them create alternatives to the traditional ways of problem solving and conducting research. For example, one researcher from robotics team used a negation strategy by asking "*what if we do not focus on people's working conditions/environments*" to suggest alternative approaches to the team's complex problem. All teams were asked to share their concepts, consider the concepts of the other research team member, and together propose an ambitious science goal that collectively represented the most disruptive concept. Participants were able to generate disruptive concepts in the time-slot of the workshop. Some of these initial propositions set up the ground for collaboration between the two teams two years after the workshop.

Table 6. Overcoming fixation moments [colour for web]

Workshop moments	Illustrative body posture	Recorded dialogue
Moment 1: High confidence in prior knowledge		**P25:** "Our context [moonshot] was: [explanation of the moon shot] … Our first variation on value is instead of distributed infrastructure; it will be more of a localised assembly …"
Moment 2: Interjection – challenging fixation		**P18:** I guess the alternative is to [description of alternative] **P25:** Yes, but the environment we are working on is unstructured … *we can't design an environment to that* **P18:** … a way to link the 3D printing biomaterials into your problem is if [present alternative] … rather than the traditional way … **P25:** *Certainly overlap but I wouldn't say …*
Moment 3: Shift in thinking		**P18:** So the perception of the environment is the hard bit, right? **P25:** *No not really* **P18:** Yeah, but imagine if the robot has a flight or fight inherited … **P25: Right!**

Principles of concept exploration helped to deal with technical barriers such as the time taken to align expectations, technical uncertainties, and lack of expertise on how to approach the problem. Participants' comments at this stage included "robotics and 4d printing scientists at work", and "make sure the object is specific enough" (see Table 5: PT13, PT2, PT28, PT30, PT4, PT25, PT22).

Through concept exploration, participants, particularly those more senior, were encouraged to see transformative potential in a new collaboration (Sen, 2014). For example, PT23 (Table 5). An established researcher saw the transformative potential of knowledge sharing and concept exploration through the creation of "high flies" and "moonshots". The phrases "great method" and "surprising insights" also reveal that the knowledge-sharing process helped participants overcome the barriers of a lack of complexity and depth of the research problem.

Not all researchers initially felt they had much to gain from a design workshop, with one commenting, "*I was an empty vessel hoping to be filled …*" (PT25). However, as Table 5 indicates, one researcher experienced a shift as the workshop progressed, from "*the day started as a blank post-it*" to "*progressed to a whole lot of great ideas*" (PT28).

Additionally, other researchers noted that the concept exploration activity encouraged group perseverance, "*We probably would have had the third attempt if time had allowed*" (PT12, Table 5). This suggests the concept exploration principle has the potential to assist participants in science collaborations to overcome the time and technical barriers encountered in the longitudinal study.

4.3. *Mindful deviation*

To overcome potential fixations, an activity focused on mindful deviation occurred in the second part of the workshop. Participants shared their groups' promising research ideas, including the technical barriers and enablers, to get feedback on alternatives to the identified barriers from the whole group.

Table 6 exhibits moments at the workshop where an individual's disciplinary knowledge fixation was challenged by the group. The group relied on structured activities of mindful deviation to challenge different assumptions. As shown in the body-language analysis, this moment provides a striking example of how mindful deviation can be used to overcome fixation.

For example, as Moment 1 in Table 6 depicts, P25 expressed his prior knowledge through an open and expansive posture. According to Carney et al. (2010), an expansive posture is a nonverbal universal pose linked to one's sense of high confidence, which, in this case, refers to PS5's confidence in his prior knowledge. Moment 2 illustrates an interjection (underlined) during the discussion. Here, P25's conceptualisation is challenged with a consequent shifting in body posture towards a more closed-limbs position, less-expansive pose, reflecting less confidence in the prior knowledge (Carney et al., 2005, 2010; Hall et al., 2005). This challenge results in P25 categorically defending his prior knowledge, blocking the alternative as indicated in the italics, with words such as "cannot" and "but".

In Moment 3, after further interjections (*italics*), P25 shifts his body language into a reflective body posture indicating the interjections led to a shift in thinking. This internal shift is captured in the affirmative word "right" (**bolded**), where P25 appears to be more open to the ideas suggested by P18. While P25, an established scientist, may have found this activity challenging, others in the same group experienced this exercise as both "fun" and one that enabled participants to "think differently for more creative ideas" (PT26).

Mindful deviation and concept exploration boosted participants' confidence in exploring technical uncertainties, as illustrated in comments like "*alone you go fast but together we go further*" (PT1, PT4, PT28), "*some light amidst the depths*" (PT30), and "*learning to think differently for more creative ideas*" (PT26). In turn, these helped participants align their technical knowledge, which we had identified as a barrier to collaboration.

Furthermore, the design principles shifted participants' attitudes towards collaboration. This is seen in PT4 "*join[ing] in discussion*", PT8 stating "*the team enjoys refining the words that crystallize our chosen concept*", and PT13 noting that the day "*progressed to a whole lot of great ideas*". The most striking example of de-fixation was seen in the analysis of Table 6, where a senior scientist, P25, went from a position of certainty of knowledge (expansive position) to uncertainty, when a more junior scientist, P18, interjected (a more closed-limb, less-expansive pose) to finally acceptance that a new and un-thought of (by him) idea might offer a solution (a reflective body posture).

5. Discussion and contribution

Microfoundation theory allowed us to unpack the individuals' attitudes, behaviours and interrelationships that contribute to broader organisational outcomes of a MO research project. We argue that design principles of knowledge mapping, concept exploration and mindful deviation positively enhanced individuals' affective behaviours, creativity, and collaborative goal-seeking directionality. This paper contributes to the literature on MO research by bringing further clarity on the potential roles of design principles in shaping the microfoundations of MO research. In particular we connect the literatures on the microfoundations of interdisciplinarity to design by illustrating how targeted design principles support the microfoundational capacities needed to address a mission (Schmidt and van der Sijde, 2022).

As Mazzucato (2018, 2020) notes, missions are inherently enacted through bottom-up processes. In this study, bottom-up processes were designed as a "fun" pathway to "learning to think differently for more creative ideas", reinforcing Aversa et al.'s (2021) observation that creating shared emotional energy supports team formation. Focusing on microfoundations helped us to clarify the connections between individual behaviours and capacities, organisations, and larger systems contributing to the MO research approach. By unpacking how design principles helped participants overcome barriers for interdisciplinary collaboration, this study advances our understanding of the microfoundations for mission-oriented research projects. More specifically, we illustrate how design principles of knowledge mapping, concept exploration and knowledge deviation operate at the microfoundational level of individual experience to overcome the barriers to collaboration in mission-oriented research. We discuss these principles below.

First, by building on the knowledge mapping design principle, participants shared their individual expertise by drawing on their motives for establishing a collaboration. Motives act as a driving force and provide "an affectively-based tendency that orients individuals toward domain-specific … stimuli" (Elliot, 2006, p. 113). Mapping participants' knowledge through their research area and interests may lead to positive attitudes to develop social and hence collaborative bonds (Gable, 2006). In other words, knowledge mapping was an efficient mechanism to overcome barriers of knowledge misalignment, miscommunication, disciplinary silos and inability to access technical knowledge. Drawing on an individuals' motivations builds empathy, boosting participants' interests in collaborative innovation processes (Price et al., 2015). In turn, addressing motivations in an initial phase of collaboration may help to overcome barriers "to common knowledge and expertise levels" in cross-organisational interdisciplinary contexts (Lam and Lambermont-Ford, 2010, p. 57). Knowledge mapping design principles tap into individuals' intrinsic motivations that encourage positive attitudes towards forming social bonds and shared emotional energy, therefore, engendering inter-disciplinary collaboration (Elliot, 2006; Gable, 2006; Lam and Lambermont-Ford, 2010; Aversa et al., 2021), which is vital for MO research.

Second, concept exploration such as negation, inversion and abstraction enabled participants to bridge different disciplines in innovative and enjoyable ways. Established scientists often consolidate and institutionalise knowledge in academic and professional disciplines (Crilly, 2015; Sio et al., 2015; Plantec et al., 2019). This may reinforce a closed system of belief, action and practice, potentially blocking innovation (Madanipour, 2013). A structured design approach that builds on concept exploration can be of use in opening such closed systems (Guertler et al., 2020), thereby helping participants break through self-reinforcing prior knowledge. Concept exploration allows for MO research interdisciplinary bottom-up solutions and experimentations (Gibbons, 1994; Kostoff et al., 2004; Schmickl and Kieser, 2008; Hacklin and Wallin, 2013; Hamann et al., 2016; Mazzucato, 2018, 2021).

Third, the principle of mindful deviation encouraged creative exploration by challenging some participants to revise their fixated knowledge and force them to explore beyond their disciplinary and institutional roles and domains. Fixation is an example of the limiting effects of institutionalised knowledge (Crilly, 2015; Sio et al., 2015; Plantec et al., 2019). Such microfoundational fixation can impede organisational attempts to achieve a mission. In our study, there were several examples – some more striking than others – of where collaboration and team formation barriers were addressed through mindful deviation. For example, there were the barriers of knowledge misalignment and the inability to tap into other's technical knowledge due to individual seniority in an institution that can become a block to innovation (Madanipour, 2013). The photo-task analysis revealed that some established scientists initially viewed the day "as a blank post-it" (PT28), and that they were "an empty vessel hoping to be filled" (PT25), indicating an initial scepticism or lack of interest in engaging in the collaboration process (Elliot, 2006; Gable, 2006). Overcoming fixation is vital for enacting the microfoundations of MO research. 'Un-fixated' individuals lead the way to creative processes, and innovative solutions (Mazzucato, 2018, 2021).

Both concept exploration and mindful deviation shifted some participants' responses, opening the potential for collaboration (Guertler et al., 2020). Knowledge mapping and concept exploration helped participants overcome disciplinary silos, develop a common language, align knowledge and generate deep, complex concepts in the time-slot of the workshop, as Table 5 indicates (PT 1, PT 8, PT 3, PT 23, PT22). Time barriers, found across SfTI's science teams in the longitudinal study, were also echoed by PT22. We argue that a designed approach to microfoundational behaviours can address organisational collaboration barriers in an efficient and creative manner.

Overall our findings indicate how knowledge mapping positions participants' motivations at the forefront of the collaboration process, fueling positive attitudes towards forming social bonds and fostering emotional energy for conducting mission-oriented science. Concept exploration enables participants to create alternatives to their fixed approaches, paired with affectively based experiences such as "passion", "enthusiasm", "humour", and "pleasure" while drawing on the necessary technical "depth" to sustain perseverance and potential collaboration. Mindful deviation fosters collaboration by flattening institutional hierarchies and helping individuals unfix from institutional roles and knowledge that can act as a barrier to innovation.

We argue that our findings complement and deepen empirically driven microfoundational research (Carlile, 2004; Hadorn et al., 2008; Crilly, 2015) by unpacking the specific role of design principles in inducing the behaviours that are essential to advancing mission-oriented research collaborations.

6. Conclusion and limitations

In this study, we explored how design principles support microfoundations of MO interdisciplinary collaborations. Our analysis shows that design-led principles and a formalised approach not only played a positive role in helping individuals overcome barriers to cross-organisation interdisciplinary research in a surprisingly short amount of time but also did so in a way that enabled thinking "differently" and generating "creative ideas".

As a human-centred design approach, C-K design principles enable institutional microfoundational capacities to address mission-oriented science across organisations and disciplines, by guiding individual behaviour and skills through a structured set of activities (Hooge et al., 2016; Hatchuel et al., 2018). Our analysis showed that design principles can offer a formalised structure that enhances creativity thereby providing the collaborative direction to bottom-up innovation necessary to address societal missions (Agogué et al., 2012; Agogué and Kazakçi, 2014; Schmidt and van der Sijde, 2022).

This research explores how the design principles can support mission-oriented science goals. As we noted, there are other design methods with their own sets of principles that may also achieve similar objectives at the microfoundational level. Therefore, we suggest that comparative studies of design approaches that centre on microfoundational analysis are warranted. Additionally, while the focus of this study is on one workshop, analysis of what happened next – that is, the longitudinal impact of such workshops on individuals as they establish collaborations for mission research – is also desirable. Data collected from other mission-led projects might complement our analysis of the barriers that occur in inter-disciplinary settings.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Therefore, we have no conflicts of interest to disclose.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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