A sociomaterial perspective on epistemic objects in design practice

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Digital technologies enable realistic and highly refined representations early in the design process, yet designers frequently use rudimentary objects in their design practice. This research proposes a framework to explain characteristics of objects that make them appropriate for different roles in complex design projects. Objects created by designers in three research settings are explored through interviews. Through the lens of sociomateriality, objects are seen in roles of joining conversation across knowledge boundaries or encapsulating conversation. Four characteristics of fidelity, investment, ambiguity, and history are proposed to determine which role an object is suited to. The framework helps explain and guide effective use of technology and appropriate use of objects in design.

Keywords: design practice, technical object, epistemic object, prototypes, sociomateriality

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Design practice typically involves creating and using material objects. Material representations help designers formulate ideas and solve problems (Brereton, 2004) but also demystify the design process for non-designers (Grigg, 2020). In particular, *epistemic objects* often feature in accounts of design practice (Miettenen & Virkkunen, 2005; Ewenstein & Whyte, 2009; Werle & Seidl, 2015). These are defined as partially expressed objects "characterized by lack and incompleteness" (Ewenstein & Whyte, 2009, p. 10). They are often rough, rudimentary, and even unattractive. Designers strive to create beautiful objects for their clients, which raises the question of why they also persist in creating and sharing ugly and incomplete objects.

www.elsevier.com/locate/destud
0142-694X *Design Studies* **87** (2023) 101201
https://doi.org/10.1016/j.destud.2023.101201

Brown (2008, p. 87) describes a design team trying to understand an instrument described by a surgeon. At a point of impasse, a designer "grabbed a whiteboard marker, a film canister, and a clothespin and taped them together … with his rudimentary prototype in hand, the surgeons were able to be much more precise about what the ultimate design should accomplish." An even more rudimentary epistemic object is encountered in the origin story of the Sony Walkman: "the engineer leading the development team brought in a small block of wood which he placed before his colleagues with the explanation that this was the size to be achieved" (Leonard-Barton, 1991, p. 65).

In both of these examples, there are conversations between different groups of people — designers and surgeons or a lead engineer and a team — with different understandings of a task and different fields of expertise. In such situations, epistemic objects can help create a shared understanding, and their rudimentary nature seems to enable them to assume a quasi-animate role; Leonard-Barton posits that "the block of wood speaks" (p. 61). This resonates with Hutchins' (1995) view of cultural systems in which people and technologies cooperate. People think "with and through" material objects (Markauskaite & Goodyear, 2017, p. 200) and with each other in distributed systems (Brereton, 2004). Understanding objects can help in managing design projects that require collaboration between people from different backgrounds and organizations.

Despite their importance in design practice, the visual and material aspects of work and objects are often undervalued in studies of organizations. Moreover, even if the importance of objects in social interactions is recognized (Orlikowski & Scott, 2008), there is less understanding of the importance that visual and material form plays in organizations (Ravasi & Stigliani, 2012; Stigliani & Ravasi, 2012). Meanwhile, studies of design, which do focus on material practices, may "focus primarily on the individual" (Bucciarelli, 2002, p. 219) and less on the social aspects of design, particularly across professional boundaries. Objects can help to bridge the gap between the concrete and the abstract (Rheinberger, 1997) because they simultaneously have a concrete form and can represent abstract concepts or objects that do not yet exist. However, we lack an understanding of the characteristics of these objects and the roles they can play in complex design projects. Thus, we examine the following two research questions.

RQ1— *what sociomaterial characteristics do objects created in complex design projects possess?*

RQ2— *what social roles can objects play in complex design projects?*

Considering people and objects together can be achieved through the theoretical lens of *sociomateriality* (Orlikowski, 2007) and its overarching practice theory framework. Sociomateriality looks at practices from the view that the social and the material are "inextricably related — there is no social that is not also material, and no material that is not also social" (Orlikowski, 2007, p. 1437). Sociomateriality falls under the umbrella of practice theory, which has been used extensively in studies of organizations to understand the routine nature of work and interaction. This perspective encourages a focus on people, processes, and objects as an integrated system and enables explanations of the roles objects play. Such systems are also present in conceptions of distributed cognition, in which objects and communities mediate and generate repeating patterns of action (Cole & Engeström, 1993).

This research investigates the interaction between social and material aspects of design practice in complex, multi-stakeholder projects. Specifically, it focuses on the perceptions and meanings attributed to the epistemic objects created within these projects. Prior research has considered how people interact with things and with other people using ethnography and ethnomethodology (Luck, 2007, 2010). These methods can reveal *what* people do but can only speculate about *why*. Design researchers typically either treat the internal workings of a designer's mind as unknowable (Brereton, 2004) or reflect on their own practices and speculate about those of others (Grigg, 2020). In this research, we rely on designers' own explanations and interpretations rather than making assumptions about the reasons underlying their practices.

The main contribution of this research is a theoretical framework explaining the social roles of objects as *joining conversation* or *encapsulating conversation*. These represent the sociomaterial aspects of people's interactions with and through the objects they create within design practice. Four characteristics of objects are identified: *fidelity, investment, ambiguity,* and *history*, each of which appears on a continuum from low to high. In combination, the characteristics and roles help guide the appropriate use of objects and effective use of technologies in complex design projects, allowing individual preferences for design tools to be understood and used effectively.

1 Theoretical background

1.1 Design practice and epistemic boundaries

Design traditionally refers to the practices used by professional designers as they shape the form of material objects (Tonkinwise, 2011; Verganti, Dell'Era, & Swan, 2021). Design interacts with a situation to understand problems — that can be *wicked* (Burke & Wolf, 2020; Camillus, 2008; Rittel & Webber, 1973) or *messy* (Ackoff, 1981) — by proposing, testing, and evolving solutions (Dorst, 2011; Hatchuel & Weil, 2009; Schön, 1983). Crucial in this process is engaging various stakeholders, each of whom possesses a unique understanding of the problem and a particular piece of the solution (Buchanan, 1992; Camillus, 2008). A challenge is framing the problem and giving all stakeholders agency to enable their contributions (Murphy et al., 2021). Another challenge is communication across *epistemic boundaries*, such as those often encountered between professionals and amateurs or clients and designers (Comi et al., 2019; Paton & Dorst, 2011; Star & Griesemer, 1989).

Subject experts typically share a common set of practices and vocabulary that allows them to collaborate but can alienate non-experts (Langley et al., 2019; Star & Griesemer, 1989). Although much research has focused on codifying these epistemic boundaries, they are not immutable and well-defined but instead socially constructed and can be reconstructed through boundary work (Langley et al., 2019). This includes using objects that are open to interpretation — namely epistemic objects (Knorr Cetina, 1981) — in order to create, align or negotiate boundaries (Leonardi et al., 2019) and iteratively narrow and broaden the focus to nurture a shared vision (Comi et al., 2019). Following Comi and Whyte (2017), a design process can be understood as a collective process of *future making*. Within this process, a range of objects is used for *imagining, testing, stabilizing,* and finally *reifying* visions of the future. The objects increase in fidelity and refinement as the ideas they represent become more concrete. Objects are central to design practice but the interaction between people and objects is also crucial in any distributed work (Hollan et al., 2000). This is increasingly the case in a world where people and digital technologies combine in almost all tasks. The role of tools, technologies and other material objects is important in understanding how people work together and the practices they develop based on communities and cultures (Cole & Engeström, 1993). Drawing on the lens of sociomateriality and the overarching framework of practice theory offers a helpful framing.

1.2 Practice theory

For some time, sociologists have focused on practices in addition to other social constructs, such as structures and systems (Schatzki, 2001). Building particularly on the work of Bourdieu (1977) and Giddens (1984), practice theory, or praxeology (Nicolini, 2012), seeks generalizable accounts of what people do, which offer explanations of social life. In general, practice theory "conceives of practices as embodied, materially mediated arrays of human activity centrally organized around shared practical understanding" (Schatzki, 2001, p. 11). A practice lens treats activity and understanding as closely related, situated (Suchman, 1987) in the social and physical contexts they occur in, and distributed among actors. In setting out a view of strategy as practice, for example, Jarzabkowski (2005) describes distributed work in organizations in terms of complex social activities involving multiple actors. Each actor has only partial knowledge, so no single actor is able to understand or perform an activity alone. It is difficult to see them as actors if a rigid structure completely controls them, yet it is difficult to imagine them acting in a coordinated manner if they are completely independent. Giddens (1984) addresses this dilemma through the duality of structure, which suggests practices both recreate structures and create them. Actors follow rules and interpretations governed by structure, but their actions can also shape or alter the structure. For example, written language provides the structure to regulate how people speak, but over time, changes in spoken language result in changes to this structure, such as new words or usage in the dictionary. The concept of *habitus* (Bourdieu, 1990) allows sociologists to explain the routines inherent in practice by situating them within social contexts. Habitus is akin to a predisposition or sensitivity to structures that allow these structures to be reproduced and maintained, like a "feel for the game experienced in sport" (Nicolini, 2012, p. 55). Rather than a set of rigid, formalized rules, Bourdieu suggests that habitus develops through social interactions, which are experienced, internalized, and subsequently shape behavior. This resonates with situated accounts of design practice, in which what designers do is explained by what they have experienced in the past, such that they interpret problems in light of their prior experience and reinterpret their experience in light of current situations (Gero & Kannengiesser, 2004). It also ensures that much of the accepted practices are tacit in nature and difficult to separate from individual preferences and idiosyncrasies.

The idea that practices are distributed as well as situated means that the social backgrounds that shape habitus have a value in society, which is expressed as cultural capital (Bourdieu, 1986). People *embody* cultural capital, which governs how they understand and practice, while the objects they create and use *objectify* cultural capital. This means that, due to differing backgrounds, people interpret and value cultural artifacts differently - one person's music or art is another's noise or nonsense. A practice lens allows a focus on objects and their role in shaping social practices and structures. Or as Nicolini argues, "if you want to understand the social, you have to go and look at what people do, what they talk about, and what they handle while talking." (Nicolini, 2012, p. 53).

1.3 Sociomateriality

Sociomateriality seeks to place material objects on an equal footing with social interaction. Focusing on the social, researchers may treat material things and technologies as marginal, irrelevant, or even invisible (Preda, 1999). For example, studies of organizations may focus solely on humans. Alternatively, they view technologies as *exogenous forces*, seeking statistical generalizations or predictions about how they relate to organizations (Orlikowski, 2010). There is a tendency to treat technologies as "black boxes" that always work as planned, but which rarely happens in practice. For example, results differ when new technologies such as 3D printing are introduced because their effective use is not always understood (Candi & Beltagui, 2019).

Sociomateriality is increasingly applied in fields such as organization theory, the social construction of technology, and particularly information systems (Boxenbaum et al. 2018; Carlile et al. 2013; Leonardi, 2013). It builds on philosophical arguments that the separation of the social and material is artificial and unhelpful (Barad, 2003). Instead, it argues that understandings of technology are "neither fixed nor universal, but that they emerge from situated and reciprocal processes of interpreting and interacting with particular artifacts over time" (Orlikowski, 2010, p. 131). Sociomateriality considers the relationship between people and objects to be one of *entanglement* or, like overlapping roof tiles, *imbrication* (Leonardi, 2013). This view rests on the controversial position that material objects possess agency, although it is not the same as "ascribing intentions, aims and purposeful action to artifacts ... [but aims at] analyzing both human actors and artifacts as generators of practical knowledge" (Preda, 1999, p. 357). Such a position helps to explain accounts of design practice, which show a close and reciprocal, almost *conversational* relationship between designer, situation (Gero & Kannengiesser, 2004), and object (Schön, 1983). In explaining their thinking, designers even refer to objects explicitly as conversation starters (Lloyd & Snelders, 2003), ascribing agency to objects in their interactions with people.

1.4 Epistemic objects

In design practice, concepts can be represented through various objects, but the practices around their creation and use may determine whether they help or hinder shared understanding across boundaries (Seidel & O'Mahony, 2014). The term *boundary object* (Star & Griesemer, 1989) is often used to describe material objects that facilitate knowledge exchange among different groups. However, limited attention has been paid by organization scholars to the form of these objects and their creation. Based on the work of Rheinberger (1997; 2010), two related categories of objects can be defined. *Epistemic objects* (Miettenen & Virkkunen, 2005; Ewenstein & Whyte, 2009; Werle & Seidl, 2015) are unstable and evolving. This means that their visual and material form, as well as their meanings, are negotiated among stakeholders in design practice and are perpetually in flux (Comi & Whyte, 2017; Ewenstein & Whyte, 2009). In contrast, *technical objects* "make possible and constrain the grip on epistemic objects. They require a certain measure of rigidity and precision in order to keep the vagueness of [epistemic objects] at a sub-critical level" (Rheinberger, 2011, p. 313). Whereas epistemic objects are open to experimentation and can be shaped by people, technical objects are more fixed in their meaning and form. They are *reified* (Bachelard, 1949) and represent what is known.

Rheinberger discusses the role of lab notes in the development of scientific knowledge, focusing on the over-looked but vital role of "scribbles" (2010; p. 330), which reveal a different picture from the ordered and logical presentation of science in published articles. He described these scribbles, notes, and margin writing as the *redimensionalization* of laboratory experiments. Capturing what happens in space and time onto a "handy, transportable form … facilitates exploration of new ways of ordering an arranging data" (p. 332) and is not merely recording or reproducing. Similarly, Matthews et al. (2021) document the performative nature of working with sticky notes, arguing that actions "are not simply actions performed to/with the note qua note, but with the idea that has been inscribed on it … the actions-with-the material are always actions-in-a-social-context" (p. 5). In both examples, ideas are not final but are reinterpreted and reorganized, in a social context and material form.

The incompleteness of epistemic objects answers and raises questions in an ongoing exploration. In contrast, a technical object, such as a detailed brief, limits the need for exploration and a designer's opportunity to create (Paton & Dorst, 2011). Meanwhile, epistemic objects, such as rough sketches (Ewenstein & Whyte, 2009), stories, or simple representations of concepts (Seidel & O'Mahony, 2014) are used because they are deliberately incomplete (Garud et al., 2008), open to interpretation and actively invite contributions from stakeholders. Luck (2010) suggests that within a design team, a design concept can have agency, as it imposes constraints on architects designing a building. By focusing on language, the role of objects in mediating among groups of people is seen, but the form these objects take is unclear. Meanwhile, Comi et al. (2019) find that the form of objects, specifically engineering and architectural drawings, is inextricably linked to individuals' and groups' identities. Their study noted a dividing line between groups who were reluctant to engage with the technical drawings used by other groups. In this way, the form of an object can determine whether it unites or divides people working on design projects. This research explores the characteristics and sociomaterial roles of objects that can unite or divide people working on design projects.

2 Research setting and methods

To address the research questions and develop an understanding of epistemic objects in complex design projects, our research follows Nicolini's (2012) advice to look at what people do, what they talk about, and the objects they handle. The primary focus is on people's relationships with objects, which leads to an examination of the objects themselves, and individuals' reflections on their creation and use. Data were collected from three organizational settings. The motivation for the research stemmed from conversations among the authors, one of whom had led design teams in Setting 1 and had extensive experience of observing, collaborating in, and studying design work in action. In particular, curiosity about the differing approaches designers used and conflicting ideas about which tools and objects should be used stimulated investigation. For example, why do some designers insist on sketching while others avoid using a pencil? Why do some feel annoyance at CAD being used early in a project while their colleagues find virtual models preferable to physical ones? After identifying initial results in setting 1, the other two settings were used to validate and extend learning. The teams interviewed all work on similar projects but focus on different industries according to their clients. Informants in Setting 1 undertake design projects for several medical and aerospace clients, while those in Setting 2 support clients primarily in energy sectors, and informants in Setting 3 have particular expertise in advanced manufacturing technologies. The similarities and differences helped in validation as well as elaborating the results.

The lead author spent time in Setting 1 over a three-month period and conducted in-depth interviews in all three settings. The second author was deliberately not involved in the interviews to avoid bias but offered an ongoing contextual perspective as a member of the design teams from which informants were drawn. Interviews focused on the objects created and the informant's reflections on their creation, evolution, and use. Following general questions to understand each informant's background, their role in the organization, and the nature of the design projects they work on, interviews focused on the objects they use. Ahead of the interviews, each individual was asked to consider examples of the objects they use for generating, developing, and sharing ideas. These were interpreted as part of the practices of *imagining, testing, stabilizing,* and *reifying* (Comi & Whyte, 2017). The interviews probed the nature of these objects, individuals' relationships with them, the reasons for choosing particular objects over others, and their positive or negative experiences. For instance, an individual describing their use of 3D printing would be prompted to show and discuss the objects produced by this tool compared with other tools and reflect on why their colleagues might have different preferences. In addition to the specific objects they came prepared to discuss, informants identified and demonstrated examples during the interviews, presenting objects stored in the workplace to illustrate and support their views.

Much recent research has used ethnography or ethnomethodology to focus on interactions among groups of people (e.g., Ball & Christensen, 2018; McDonnell & Lloyd, 2009). Such methods allow words and gestures to be analyzed, giving a rich picture of how people and objects are involved in the design process. They also allow interactions to be studied as they happen. However, these methods may entail interpretations or assumptions about the intentions behind actions or the meanings people ascribe to events. If we assume that organizations are socially constructed and that people within them are knowledgeable (Gioia et al., 2022), then it is incumbent on researchers to understand the first-hand experiences of those people. To this end, the research emphasized informants' first-hand accounts and reflections in their own words. Additionally, speaking with individuals rather than groups makes it more feasible to identify the different perspectives involved and avoid issues such as group-think.

A data structure was created to connect individuals' accounts with a plausible and generalizable account of the phenomena under investigation (Gioia et al., 2012; Gioia et al., 2022). The theoretical lens of sociomateriality and the overarching framework of practice theory suggest that individuals, even within a team, are influenced by cultural capital and habitus. They are likely to respond differently to objects, and these objects could, therefore, divide people. Past research (Comi et al., 2019) shows that such divisions may relate to professional identities and practices, but it is less clear about how individual differences within a profession or a team would contribute. Meanwhile, the idea that objects such as a block of wood 'speak' to people suggests they can overcome differences and integrate people (Leonard-Barton, 1991). To understand such competing forces, it was essential to understand each individual, their formative background, and their relationship with objects. This follows a tradition of interviews with individual designers to understand what they were thinking in their creation and interaction with objects. An interview with the industrial designer Philipe Starck (Lloyd & Snelders, 2003) sheds light on the genesis of the famous lemon squeezer he designed and how it arose from sketches on a napkin. Meanwhile, an interview with the automotive design engineer Gordon Murray (Cross, 2011) sheds light on how the regulations in competitive motor racing inspired a series of innovations that created systemic and strategic changes. While the objects in the present research may be more modest, it was crucial to understand — in their own words — how and why individuals use them.

2.1 Data collection

Data collection and data analysis were collaborative, iterative (Locke et al., 2020), and abductive (Dubois & Gadde, 2002). They involved "cycling between emergent data, themes, concepts, and dimensions and the relevant literature" (Gioia et al., 2012, p. 21) in an iterative fashion. The approach was abductive in that it progressed bottom-up, from the data to theory, as well as top-down, from the research question to the data. Repeated discussions within the research team were instrumental in honing insights as they emerged. In the course of these discussions, a number of temporary analytic artifacts (Locke et al., 2020) were generated, including rough diagrams, lists, and partial narratives, which helped the team develop and refine an understanding of the data in light of literature. An example is shown in Appendix 2. The focus was on understanding informants' narratives through descriptions aimed at demonstrating authenticity, plausibility, and criticality, in order to convince readers (Golden-Biddle & Locke, 1993).

Informants were chosen to cover a range of seniority levels (from junior designer to principal design engineer), technological expertise, and roles (including technical experts, project managers, and design engineers), see Table 1. A criterion for including informants was their involvement in design projects, making them qualified to describe the processes followed and the interactions involved. Interviews were semi-structured, and interview questions were intended to explore each informant's approach to design, prototyping, and the creation and use of objects. The interview protocol used is shown in Appendix 1. However, the interactions and conversations were guided by informants, and the insights their demonstrated objects and described experiences revealed. In total, 26 ½ hours of interactions were recorded and transcribed, and 300,000 words of data were coded. While images or videos of objects were included in the data for analysis, in most cases, these could not be shared beyond the research team for anonymity reasons. However, Figures 2-5 show some examples of the objects shared by informants, for which permission was given to include them in this paper.

2.2 Data analysis

The first set of observations and interviews (in Setting 1) formed impressions that could not be clearly articulated prior to coding (Huising, 2015) but were developed by moving between literature and further empirical data. As an example, emerging themes included a suggestion that rudimentary physical prototypes (or epistemic objects) created with LEGO® or 3D printing are more helpful than more refined digital CAD models, even though 3D printing requires a CAD model. Additionally, a conflict between CAD and sketching and alternative positions on which of these constrains or allows freedom of expression appeared. Moreover, an *in-vivo* code, the suggestion that some tools are *"a bit too good"* (A), seemed powerful. Revisiting the literature helped to expand these initial impressions and sharpen the theoretical framework. For example, the idea that epistemic objects are effective precisely because of their lack of refinement, in comparison with reified, technical objects. Informants in Settings 2 and 3 were presented with the proposition that some tools (including CAD) are *too good* because they reinforce boundaries. Their responses, such as *"I've never considered it, but I agree wholeheartedly"* (Y), helped validate and extend the early results. For example, V's description of simple representations helping a team to progress ideas led to an understanding of how simple objects leave space for interpretation and allow one's mind to fill in the blanks with possible alternatives. Returning once again to the literature, the idea of material objects possessing agency (Hutchins, 1995), embodying culture and the duality of their structure (Bourdieu, 1986; Boxenbaum et al., 2018; Giddens, 1984) could be considered as explanations, and helped frame the results around objects joining a conversation with designers.

Table 1 Informants and their job roles.

Setting	*Label*	*Job role*[a]	*Recording duration*[b]
1	A	Design Engineer	58:19
1	B	Engineer	58:47
1	C	Design Engineer	56:00
1	D	Design Engineer	53:21
1	E	Engineer	61:57
1	F	Engineer	69:34
1	G	Project Manager	64:13
1	H	Engineer	65:13
1	I	Design Engineer	53:31
1	J	Design Engineer	66:39
1	K	Project Manager	55:36
1	L	Project Manager	73:05
1	M	Design Manager	39:40
1	N	Project Manager	68:30
1	O	Design Engineer	58:34
1	P	Design and Development Engineer	62:27
2	Q	Product Design Team Leader	50:24
2	R	Senior R&D Engineer	66:24
2	S	Senior Design Engineer	59:43
2	T	Manufacturing Engineer	56:27
2	U	Design Engineer	24:54
3	V	Design Research Engineer	69:37
3	W	Senior Design Research Engineer	85:25
3	X	Graduate Design Research Engineer	59:35
3	Y	Technical Specialist	74:06
3	Z	Design Research Engineer	79:20

[a] Actual job titles have been edited to ensure anonymity.
[b] Interviews were scheduled to last 1 h, although some exceeded this time and informants asked for some parts not to be recorded.

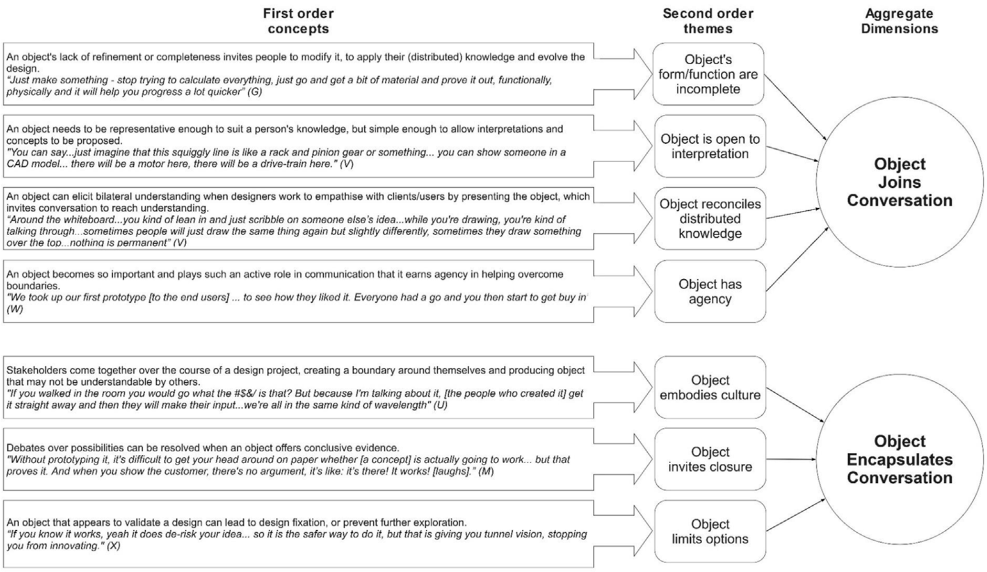

Figure 1 Data structure resulting from analysis of the data using the Gioia et al. (2012) method

Epistemic objects and sociomateriality

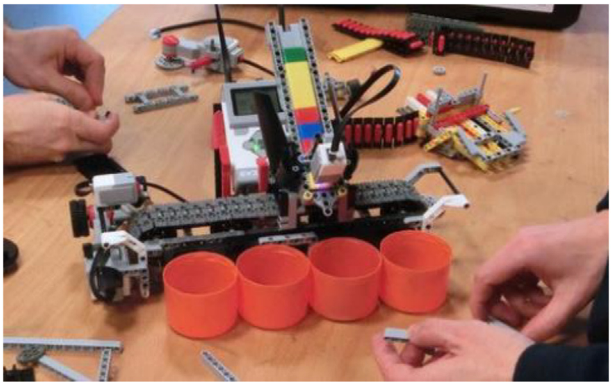

Figure 2 Construction toys enable the quick and cheap creation of objects that aid experimentation with design concepts

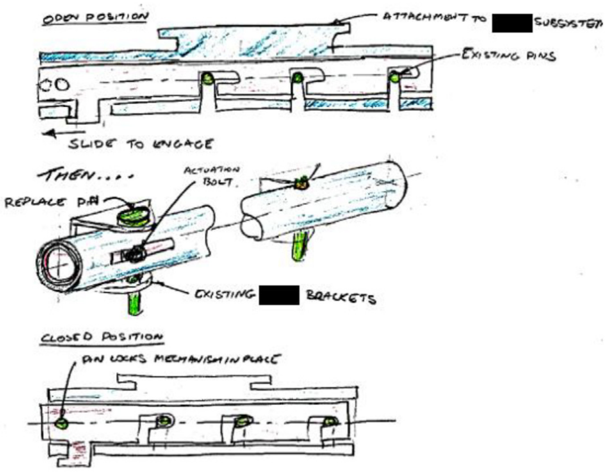

Figure 3 sketch of a design concept showing proposed dynamic movements

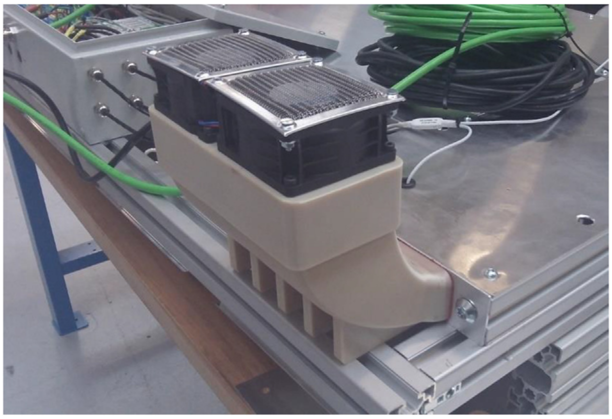

Figure 4 an object created using a combination of 3D printing and available "junk"

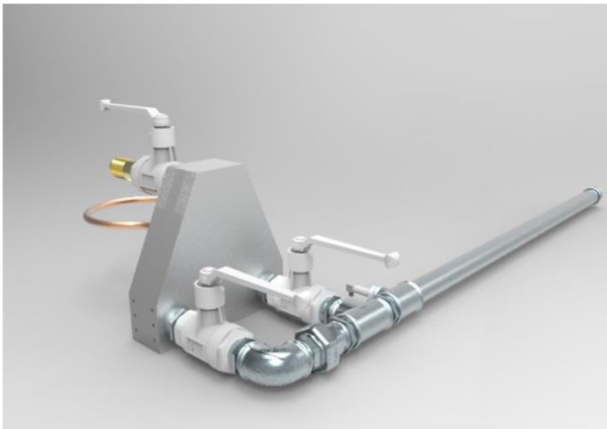

Figure 5 A rendered CAD model.

Following each site visit, observation, or interview, notes and initial impressions were shared with the research team, which helped with interpretation, coding, and refinement. For further validation, discussions with practicing designers, who had not been part of the main study, confirmed the plausibility of the results, which are discussed in the next section. Each of the three authors played a specific role in data collection and analysis. The first author conducted the on-site visits and a total of 26 semi-structured interviews (see Table 1). The second author was a participant observer in Setting 1 as well as collaborating over a number of years with counterparts in the other two settings. This involvement helped to ensure the validity of interpretations at the outset of the research. The third author participated in the analysis of the data — including photographs of objects and design settings as well as interview transcripts — introducing the perspective of an outsider investigating empirical contexts (Burke & Wolf, 2020; Evered & Louis, 1981). The third author endeavored to challenge the assumptions and interpretations of the other authors by offering alternatives for discussion. Once the research team had reached their conclusions, they were shared with informants in follow-up conversations (in-person or electronically). They were invited to comment on the results as well as approve the use of their words and images. Informants responded to the effect that they felt the interpretations were original, fair, and trustworthy (Guba & Lincoln, 2005).

The research questions relate to the characteristics of and sociomaterial roles played by objects in design practice, so it was essential to understand informants' worldviews and interpretations in their own words. The Gioia method (Gioia et al., 2012) was used to create the data structure shown in Figure 1, demonstrating the evidence chain that leads to the theoretical results. This connects first-order codes based on the evidence from informants with second-order themes based on researchers' interpretations. To communicate and demonstrate examples, direct quotes are used, supported by examples of the images and objects that informants shared as part of the research.

3 Results

Objects that were observed and discussed were categorized according to the practices or technologies used to create them. These ranged from hand-drawn sketches; toy models built using construction toys such as LEGO and MECCANO®; fabricated models, using both 3D printing and traditional fabrication; and computer models, primarily Virtual Reality (VR), Computer Aided Design (CAD) or simulations and tools such as Topology Optimization. Objects were classified within Comi and Whyte's (2017) stages of design evolution, from imagining, through to stabilizing and reifying. Instances of all four purposes could be identified for all the types of objects, from VR and CAD for imagining to toy models for stabilizing. The analysis sought to explain this surprising observation. Informants were asked to discuss the nature of the design projects they worked on, as well as the clients and colleagues they worked with, and to reflect on how they used different objects, tools and technologies within their design practice.

3.1 Design projects

Informants in all three settings described design projects that begin with a client request, followed by a project scope that can vary in its precision and formality. Knowledge boundaries between client and team must be overcome for the project to progress. Such boundaries also exist among the team members whose experience and approach to design may limit collaboration. The boundaries shift during projects when the design team and the client work together to explore the problem and develop solutions. The objects they create and the use of these objects are crucial in these processes. In all cases, the projects tend to involve implementing or creating new technologies and working at a low Technology Readiness Level (TRL), which creates uncertainty and limits the scope of projects:

> *"The main problem with scoping out design projects is that you are starting from a low TRL … you don't know really what the solution is going to be … I've tended to only quote and scope out in detail the first concept phase … sketches and so on, make some cardboard models … and leave phase two TBC" (G)*

Projects vary within and among the three settings but in all cases, focus on design up to and including pre-production prototypes, but not volume production. Within these contexts, a wide range of design representations are used not only as the output but throughout the design process.

3.1.1 *Setting one*

Typical projects in Setting 1 include early-stage concept design, proof of concept and pre-production prototypes for medical, aerospace and other contexts. Clients may be large organizations, with tightly defined development processes or small businesses with limited experience of development. In some cases the client has a specific design problem or context but a lack of clarity over technical requirements or users.

> *"… [clients] don't have the knowledge of what the end user needs so … there are at times a fairly conflicting set of requirements". (A)*

Two particular features of design in this setting were the need to reveal constraints and to create innovative solutions to these constraints. For both reasons, an emphasis on fabricated models, using 3D printing or workshop materials was evident. Informants reported creating objects that would help them understand how mechanisms could work as well as to share ideas with clients. In one particular example, a proposed solution had to be revised when a previously overlooked safety restriction was identified, in part because a scale model was shared with the client. Another prominent characteristic in this setting was the use of construction toys such as LEGO® and MECCANO® to not only represent and communicate but indeed to help a designer imagine a mechanism and create functionality in a concept design. A similar approach was taken by some informants using computer tools, particularly Virtual Reality (VR), for creating and manipulating concepts in an experiential environment.

3.1.2 *Setting two*

Projects in this setting are often complex due to a range of constraints that are often not recognized by clients, and which the team must identify:

> *"… you need people to be aware of the hierarchy of requirements from … laws, regulations and then standards and then contractual requirements" (Q)*

Clients may lack technical or commercial knowledge that the team must *"educate"* (Q) them about, creating a risk that the client *"will push back and say no, just make it the way I'm paying you to make it"* (S). In this context, a range of objects were seen to be useful both for the team to explore problems and to engage with clients to ensure cooperation. The design work reported by informants in this setting seemed more technical in nature and less suited to the use of construction toys than in the other settings. Nonetheless, the use of visual representations, both created and shared was evident, as was the use of physical models, for example to confirm sizes and locations of components:

"… if we don't have clear data on mounting holes or [acceptable dimensions] … you want to clamp it and hold it … you can kind of see it does fit definitely and … feel a bit more comfortable then going and getting it manufactured." (R)

Using physical models helps to *"inform someone that their assumptions aren't quite right … but then add value not be derogatory about it"* (S). This applies also to sharing images of existing solutions, so that designers without an *"encyclopedic knowledge of every mechanically designed thing out there"* (S) would have a shared point of reference. The shared reference was particularly noted when informants discussed how working together around a shared computer document, and particularly around a physical whiteboard, enabled their cooperation and created a shared understanding, embodied in the outputs.

3.1.3 Setting three

In this setting, design projects typically involve new technologies in production processes. An emphasis on physical models was evident in this setting, but a specific challenge relating to the social, as well as material context was in evidence. Working with team-mates, emphasizing the collaborative, visual but also embodied (Matthews et al., 2021) nature of their work, an informant described working around a whiteboard:

"you kind of lean in and just scribble on someone else's idea and think oh well, if we did this …" (T)

Informants reflected on dealing with people at different levels of client organizations. They described situations in which senior managers were drawn to automation or digital control to improve production capacity and efficiency:

"we get industrial clients who want a robot [or other technologies] … we'll look at what the problem is and [design] a solution" (Y)

Communicating with, working alongside and trying to understand operators on production lines is seen as essential for defining problems that can be solved through design rather than investing in technology. Moreover, engaging with operators but also with senior management, benefits from the use of both visual and physical representations. In some cases, *"the presentation has to be fairly good … to get the point across"* (T). Yet for physical representations where *"everyone had a go [at using a prototype]"* (T) the level of refinement is less important and indeed seems to help in developing something acceptable for users. 3D printing was again mentioned repeatedly, as a way to quickly and cheaply create something that could be shared to enable collaboration, without relying too much on aesthetics:

"its very rare that I will care about the color of a 3D printed part" (V)

3.2 Object characteristics

The projects, clients and consequently objects created differed among the three settings. However, analyzing the way these objects are used, particularly in social contexts and interactions among team members and clients we identified a consistent set of characteristics shown in Table 2: ***fidelity***, ***investment***, ***ambiguity***, and ***history***. Despite differences among the settings and the types of objects created, these characteristics were identified in each of the three settings, lending credence to their validity.

Brereton (2004) distinguishes between abstract representations that are open to interpretation and concrete ones that seek to avoid misinterpretation. For example, technical drawings "ensure that a trained machinist can interpret a drawing in only one way, so that he or she will build exactly what the designer intends" (Brereton, 2004, p. 86). Although Brereton (2004) chooses not to include a "definite" dimension since no representation of a design is final, we find the degree to which *fidelity* suggests finality is an important characteristic. On the other hand the degree of *investment* that these individuals have in the objects seems to influence their desire to further develop the design or see it reach a conclusion. We also identify *ambiguity* as a characteristic, which describes the opportunity for contributions to the evolving design. We agree with Grigg (2020) that objects reflect the *history* of their creation. In particular, "local, embodied social actions have … downstream consequences" (Matthews et al. 2021, p. 21) such that "objects are imbued with meanings … they encapsulate human motives and activities" (Markauskaite & Goodyear, 2017, p. 203). In particular, we observe the shared history created by a group of individuals is embodied by the objects they have jointly created.

3.3 Object roles

Through a process of analysis and iteration, the data structure presented in Figure 1 was developed, categorizing objects by the roles of ***joining conversation*** or ***encapsulating conversation***. Both were found to be important and valuable at the appropriate stage of a project across all three research settings but failing to recognize which is required in each situation can have negative consequences. To explain these results, the following sections present informants' words supporting researchers' explanations.

3.3.1 Object joins conversation

Tackling wicked problems requires collaboration among multiple stakeholders, the knowledge boundaries between whom may pose barriers to progress. Such barriers can manifest as a stalled conversation. Referring to the examples mentioned in the introduction, a humble block of wood or a

Table 2 four characteristics of objects observed in the research settings

Characteristics	*Definitions of characteristics*	*How each characteristic contributes to a relationship with people in design*
Fidelity	The degree to which an object seems to represent reality	A refined or apparently complete object discourages further change. Incomplete objects encourage contributions, e.g., sketches or models that suggest form/function but are clearly works in progress (Garud et al., 2008; Whyte et al., 2009).
Investment	The degree of financial, emotional, or other investments in the object to date	There is a reluctance to change a design once substantial effort has gone into the object. Experienced designers recognize the value of (rudimentary) epistemic objects for engaging stakeholders. Efforts to create (refined) technical objects may appear professional but can be counterproductive when this limits stakeholder contributions.
Ambiguity	The degree to which the functionality represented in the object is open to interpretation	An object that does not entirely demonstrate how a design will work leaves scope to imagine and propose alternatives. Alternatively, where it appears that decisions on function are finalized, stakeholders are pushed to either approve or reject the design.
History	The degree to which the object embodies a shared narrative or culture among those who have contributed to its development	An object can encapsulate the history of its development. A technical object should be self-explanatory without requiring additional knowledge. While this limits the scope for development, it should also convey the essence of the shared work. An epistemic object, although less clear, can stimulate further social interaction due to the need to explain its history.

rudimentary prototype cobbled together from odds and ends at hand can serve as a locus for collective problem-solving.

3.3.1.1 *Object form/function is incomplete*. When faced with uncertainty and a need to engage multiple stakeholders, incompleteness is a useful design principle (Garud et al., 2008). Informants described how they represented concepts and ideas quickly but incompletely. This refers either to the form, for example, a scribble that invites others to correct, improve or evolve a concept, or function, when an object suggests but does not fully achieve the intended functionality. An example from setting 1 is provided in Figure 2.

Informants described their ingenuity in combining and repurposing materials to create simple but effective models. They would *"just bolt it together and see if it works" (M) or "just knock up really rough models"* (A). Various media were mentioned and seen to afford rapid imaging, testing, and communication:

> *"I tend to build in LEGO because it's just quick, like super-quick, to just change things over, you can try things out and go no, no, that's wrong. You haven't lost any time waiting for parts to be made, I just know, I just swap out bits to just experiment with ideas." (C)*

"You're sat in a meeting with someone … scoop [the 3D printed object] up, here you go … because they don't hold any value of any sort, whereas if you … designed to the exact tolerances … it's certainly got a whole lot more IP to it, and it's got to be protected" (Y)

In the above examples, from settings 1 and 3 respectively, lack of refinement is clearly valued because it enables emergence. Moreover, it allows a shared visualization, which avoids restricting the design too early and helps stakeholders understand what is proposed and contribute ideas.

3.3.1.2 Object is open to interpretation. Incomplete objects offer opportunities for reflection and further development (Schön, 1983). This is particularly important when complex problems demand distributed problem-solving efforts involving multiple actors. Informants talked about collective activity around a whiteboard, *"you're kind of talking through the idea, explaining it as well, giving a bit of a given explanation"* (V). Sketches and the power of sketching were mentioned repeatedly (see Figure 3).

Rudimentary objects are both understood by participants and open to different interpretations. In one case from setting 3, *"although it is just like bits of plastic and there's no fans or batteries or anything, you can just … kind of imagine that a bit clearer now. It could be a physical thing"* (V). In another instance, *"If you give someone a Tupperware box and a take-away box lid that don't quite fit together, but you can see how the closing mechanism works, they can kind of understand it. If you put up a white box on a screen and a Tupperware lid on a screen and overlaid them with the wrong size. You would just be like, well, I don't really get it"* (Y). The simplicity and materiality of these models (combining 3D printed and repurposed components) allowed understanding but also imagining alternatives.

"Sometimes you can sketch the wrong thing, but actually just because that line is in a slightly different place. It just clicks, something that makes you think. Oh, hang on, instead of being to the left, that could go to the right, and that would just be an error in sketching that then makes you even think actually I could do it." (P)

"If you make it [from traditional materials] and try it out, you have to make a big leap of imagination with the object to how you would manufacture it, but it might help you make that creative leap that you wouldn't otherwise get if you, you know, tried to draw it, CAD model it, or analyze it … it's a tactile thing". (L)

Among team members with similar knowledge, there may be one common interpretation, but a lack of refinement can enable multiple interpretations to emerge and alternatives to be explored.

3.3.1.3 Object reconciles distributed knowledge. Creating objects entails a form of boundary work that helps expose and reconcile boundaries between individuals (Langley et al., 2019). A high level of refinement and technical detail may alienate actors, whereas rudimentary objects are easily understood and allow stakeholders to contribute.

For example, one informant in setting 2 compared the formality of a Failure Mode, Effects, and Criticality Analysis (FMECA) with the simplicity of a hand-drawn Ishikawa (aka fishbone) diagram.

> *"FMECA wants to be everything … a very strong document that can stand on its own legs, whereas an Ishikawa diagram [needs to] have a narrative around it once it's produced, but I think that's probably stronger because you can then use it in the discussion …. I think with the FMECA, a lot of the focus is on the document. Whereas in Ishikawa a lot of the focus is on the solution, which is probably more meaningful" (R).*

Focusing on the solution rather than refining the object was also seen as vital for engaging external stakeholders, for example, end users. When tasked with automating a manual process, an informant in setting 3 described an ethnographic approach to understanding the problem, which differed from a more technological approach.

> *"I would work on the line with the operators for a couple of days … jump in next to them and do the job so that I'm talking to them … [then I took a 3D printed] prototype so they could try it out … to see how they liked it. Everyone had a go, and you then start to get buy-in" (W)*

Two crucial aspects can be seen here. The first was the recognition that these operators, earning *"just a bit more than minimum wage, have a massive impact"* (W), and their engagement was, therefore, important. Secondly, epistemic objects were used to break down boundaries and engage them in both exploring the problem and generating a solution.

3.3.1.4 Object has agency. When individuals work together to create objects, they also generate a new, shared culture (Bechky, 2003; Sapsed & Salter, 2004) of which the object is a part. An object enables a shared understanding of problems, a distributed approach to solving them, and a shared culture to emerge. It represents a team's shared experiences in the same way as inside jokes and references that only those in the know would understand. Having been shaped by the team, the object provides a common ground.

> *"Usually [the object] is supposed to come in right at the very beginning … [to] get people thinking about problems" (J).*

For example, one project concerned *"… a valve that … had this sort of shut-off mechanism so once the fluid entered into a certain chamber you could then basically close off the entry point or exit points or open them if required"* (H). To help team members understand and engage with the problem, *"… we basically built a LEGO model"* (H). This initial, rudimentary object invited contributions. As it evolved, it held meaning for those involved in its creation (but not necessarily for those outside the team). Another example involved hand-drawn lines on a whiteboard created during a conversation. Those present in the room would *"get it straight away"* (U), while anyone who had not been involved would struggle to understand because they lacked the shared experience.

In the previous examples, incomplete, rudimentary objects helped to facilitate exchange in distributed problem-solving, and informants highlighted the importance of the materiality of these objects.

> *"You can touch it. You can poke it, you can look at it, you can see it. I don't think humans are very good at visualizing a product off of a 2D surface … The ability to pick something up and work with that in my hands is huge." (Y)*

> *"I think its human nature — people like to touch stuff … I feel massively connected to the project now because I've personally touched [the 3D printed model]." (S)*

These examples suggest emotional engagement with a design that has resulted from interacting with a material object.

When a discussion reaches an impasse, objects (e.g., Figure 4) are brought in for inspiration, almost as though a person is called in to join the meeting. This highlights the powerful role that visual and material objects can play; objects that earn agency as active participants rather than inanimate objects.

3.3.2 Object encapsulates conversation

When a design project progresses to the point that further imagining and testing yields diminishing returns, the time comes to stop experimenting and move towards stabilization and even reification. Objects also have a role in this phase, one of nudging things toward completion. The object, at this point, will encapsulate the conversations that contributed to its creation.

3.3.2.1 Object embodies culture. Objects act as a store for cultural capital (Giddens, 1984) in the sense that a representation, such as a designer's sketch, or artwork, such as a painting, follows (or deliberately manipulates) conventions that are familiar to those sharing a cultural background.

Our research revealed a cultural divide between those who turned to CAD early in a design project and those who viewed computer-generated models suspiciously as too technical, insisting that it was better to delay a preoccupation with detail.

Team members' educational background and age were cited as reasons for their preferences: *"I started off on a drawing board, so maybe it's just the way I'm programmed. Maybe somebody at 18 [years of age] would go straight into VR?"* (T). Indeed, some informants favored VR or CAD due to their greater proficiency with these tools over sketching and toy models. Younger team members scoffed at the *"... assumption that you can come up with something that's an amazing design just based on putting LEGO bricks together ..."* (D).

When dealing with clients, in particular, informants argued that before presenting a concept to a client, they must *"get it to a presentable point that might be a refined sketch in the early stages and then come up with a narrative of how you've actually got there and make that digestible for the customer, because ... they are coming at this from no design experience at all"* (U).

Thus, objects embody a particular culture and can raise barriers to conversation with those who do not belong. These boundaries are flexible and have a reciprocal relationship with objects, such that evolving one can catalyze a change in the other (Langley et al., 2019; Leonardi et al., 2019).

3.3.2.2 Object invites closure. Given the complexity of many design projects, problem-solving resembles a jigsaw puzzle in which different individuals each hold some of the pieces. Distributed problem-solving can create conflicts and differences of opinion that hinder progress. For example, in redesigning a production process, part of the issue was to convince managers what the problem actually was. After the team observed a difference between what users experienced and what managers thought:

> *"All we did was use their data. We just presented their data to them, but presented in a way that they went, yeah, I've got a problem." (Y)*

The external perspective may have been important in this example, but the data seemed even more so. The data were an object with sufficient refinement to avoid speculation and overcome differences in opinion.

In another example, a toy model was used to allay fears that a proposed mechanism would satisfy requirements:

> *"Without prototyping it, it's difficult to get your head around on paper whether [a concept] is actually going to work ... but that proves it. And when you show the customer, there's no argument, it's like: it's there! It works! [laughs]." (M)*

We noted a recurring sentiment that when communicating with external stakeholders,

> *"The presentation has got to be fairly good to get the point across ... if you use a bunch of sketches and they don't understand what it is that we're trying to get across or how it's going to work, then it's going to make it difficult" (W).*

Clients may not understand the design process, so an object is deliberately intended to be self-explanatory without requiring interpretation. However, this creates a trade-off. Whereas a simple object invites interaction, a refined one invites closure, for example, the one shown in Figure 5.

3.3.2.3 Object limits options. Design requires exploring problems by experimenting with solutions. With this in mind, low-fidelity objects, although unrealistic, are helpful since they can be created rapidly and allow experimentation. While this is also possible with CAD models, they generally limit experimentation. Firstly, the effort invested in creating a detailed CAD model means making changes *"can be very time-consuming"* (U). Secondly, high refinement and apparent accuracy can give an unrealistic impression that things must be a certain way, which may actually be unrealistic.

> *"You look at a really nice shiny fancy CAD model, and you are bang on. I want that! Well, its not gonna look like that. 'cause that's a pretty rendered picture. Oh, but I want that!" (Y)*

Concerns around CAD were echoed in cases where simulations or other algorithm-driven design tools such as CFD and FEA were applied. These tools are used to test, modify and improve designs. The increasing availability of additive manufacturing methods means that previously impossible shapes can be produced, making topology optimization algorithms part of the designer's toolkit. However, informants varied in the extent to which they trusted these tools. Experienced designers cited past projects in which incorrect assumptions led to invalid computer-generated solutions and showed why testing to confirm the results could be important. For example, Z described a motorcycle design created using a topology optimization algorithm for additive manufacturing. Despite capturing physical and technical requirements, *"they missed capturing the info from … the rider of the motorbike [who said] Oh no way … I'm not gonna ride the motorbike with that component because the appearance of the part was so weak"* (Z).

While a designer with technical experience could interpret and suggest modifications to a colleague's CAD model, a client or someone with less knowledge might see it as final. Even for designers, some suggested that *"CAD limits your ability to create … concepts. Sketching is a much more free-flowing way to explore different things. I think you can constrain yourself when you dive into a CAD package"* (G). While CAD is vital in most design projects, the inclination to rush too quickly onto a computer has its risks, most clearly where it limits applications of human creativity or restricts inputs from some stakeholders.

Despite these potential misgivings about the use of computer-generated objects, such as CAD models, they can serve the important purpose of limiting options. Whereas imagining and testing call for being open to considering multiple options, stabilizing a design requires choosing among options and limiting the consideration of further options.

4 Discussion

By considering the range of epistemic objects and technical objects observed in the case settings and their uses across project stages, we propose that these objects can either join conversation or encapsulate conversation and that four key characteristics determine which of these occurs. This is illustrated in Figure 6, which proposes relationships between characteristics and roles.

Our results shed new light on previous research. Problem framing, shared understanding, and stakeholder involvement are all important when addressing wicked problems (Murphy et al., 2021). Prior research shows how epistemic objects contribute to these objectives (Comi & Whyte, 2017) and that appropriately used objects can facilitate distributed design (Brereton, 2004) that crosses professional boundaries such as those between designers and clients. In previous research, physical representations are regarded as superior to digital ones. For example, Matthews et al. (2021), who focus on the embodied nature of sociomateriality, find virtual whiteboards to be less valuable than physical sticky notes. They point to the confusion caused by several people manipulating virtual sticky notes in Miro®. An alternative view may be simply unfamiliarity with the tools affecting their efficacy. A number of informants in our study noted the embodied aspects of working together around a physical whiteboard. On the other hand, designers who had continued working

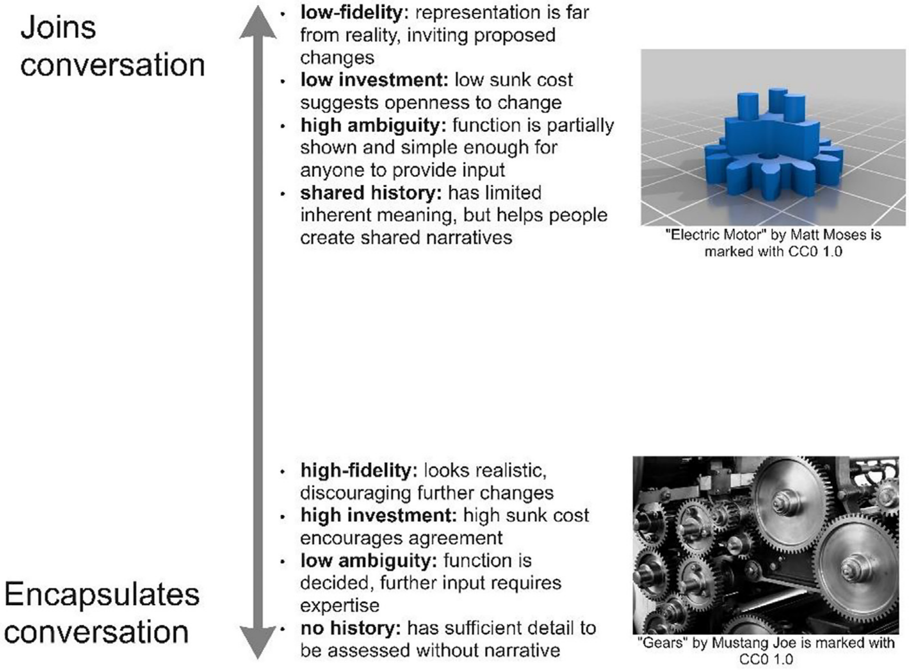

Figure 6 Social and material characteristics of objects are proposed to determine their roles in joining or encapsulating conversation

through enforced lockdowns discussed the benefits of digital tools. For example, those with access to a 3D printer were able to create physical representations of evolving designs, while others described creating makeshift models to demonstrate to clients on video calls. Considering the social aspects of distributed design, our results echo Sapsed and Salter's (2014) example, where team members in a different timezone who received a document but were not part of its creation found it much harder to relate to. We argue that the social characteristics of investment and history in Figure 6 should be given equal weight as the material characteristics of fidelity and ambiguity. Examples of rudimentary objects such as a block of wood or marker pens and film canisters appear to suggest the importance of tactile dimensions, which would make digital tools less useful. Instead, we argue that the appropriateness of these objects stems from their ability to overcome boundaries in knowledge and enable social or cultural connections to be formed. On this basis, digital tools can be effective if, as a global pandemic has demonstrated, they are accessible and useable for all stakeholders. We saw examples (as shown in appendix 2) of CAD or VR being used effectively to overcome boundaries, as well as issues caused by inappropriate use of these technologies.

Experienced designers intuitively recognize the value of epistemic objects and have the confidence to share their "night science" (Rheinberger, 2010, p. 333) or the notes, scribbles, and rough sketches from which ideas evolve. In contrast, in an effort to appear professional, less experienced designers may inadvertently use objects that represent their understanding but also restrict conversations and limit others' engagement. Such technical objects (Ewenstein & Whyte, 2009; Rheinberger, 2011) can reinforce boundaries between stakeholders and limit opportunities for creativity. Our results explain why experienced designers use epistemic objects and could help guide the effective use of digital technologies rather than blanket dismissal in the early stages of design.

By emphasizing the importance of the material and social contexts in which design work occurs, we highlight the active role that epistemic objects play in shaping design practices and outcomes. This framework can help designers be more intentional and reflective in their use of epistemic objects and can provide a foundation for future research on the complex relationship between human practices and the material world.

If design practice to address wicked problems is a distributed process, it follows that there will be boundaries preventing collaboration. We demonstrate how creating objects — epistemic objects and technical objects — is a form of boundary work (Langley et al., 2019) that helps overcome boundaries among stakeholders (Carlile, 2002; Star & Griesemer, 1989). A key finding is that the objects created in the design process can join a conversation between individuals who come together as problem-solvers. This is more likely to be successful when these objects are rudimentary (epistemic objects), whereas more refined objects (technical objects) can encapsulate (preceding) conversation and thereby reinforce the boundaries between people. This resonates with the arguments made by Ewenstein and Whyte (2009) that technical objects that stakeholders cannot interpret or engage with limit progress. It also helps to explain Carlile's (2004) observations that CAD models work in some contexts but not others.

4.1 Contributions

This research proposes a framework for understanding the characteristics and roles of objects in design. It goes beyond previous research by including 2-dimensional and 3-dimensional virtual and physical objects within the analysis. Previous research (e.g., Brereton, 2004; Matthews et al., 2021) generally argues that virtual representations, such as virtual sticky notes, are inferior to their physical counterparts. The framework presented here offers a more nuanced perspective, particularly since the research examines digital technologies such as 3D printing and VR that blur the boundaries between physical and virtual.

We offer important contributions of value for design theory and practice. First, we propose theoretical explanations for the effective use of objects in complex design projects by examining their characteristics and roles in three empirical settings. We draw on sociomaterial theory, which posits that human practices are shaped by the material and social contexts in which they occur. From this perspective, objects need not be merely passive tools used by designers but can be active participants in the design process. They shape how designers think, communicate, and collaborate with each other and with stakeholders. We draw on the theory of epistemic objects proposed by Rheinberger (1997), as well as connecting with discourses in studies of organizations and information systems around sociomateriality (Orlikowski, 2007, 2010) and practice theory (Nicolini, 2012). While studies of organizations recognize the importance of epistemic objects (Stigliani & Ravasi, 2018), they largely fall short of understanding their creation. Meanwhile, design studies focus on objects and their creation but can benefit from a sociomaterial lens and the concept of epistemic objects to explain how people in organizations interact with and through objects during design projects. Hence, our research offers a valuable contribution to the understanding of the role of epistemic objects in design practice. It provides a framework for understanding how and why different objects can be used intentionally to enable social interactions.

In response to RQ1, the framework identifies four characteristics that objects possess in complex design projects, namely, *fidelity, investment, ambiguity,* and *history*. Each of these characteristics is manifested on a spectrum ranging from low to high, and configurations of these characteristics distinguish between technical objects and epistemic objects. In response to RQ2, we propose two roles that objects can assume in complex design projects, namely *joining conversation* or *encapsulating conversation*. Designed objects, for example, Philippe Starck's famous Juicy Salif lemon squeezer (Cross, 2011; Lloyd & Snelders, 2003), are sometimes described as conversation starters. Is it possible to go one step further and suggest that objects can also be conversation participants? Can a block of wood really speak? Designers certainly engage with objects in this way when they are designing: "the designer may take account of unintended changes made in the situation…by making new moves. He shapes the situation, it "talks back" and he responds to the situation's back-talk" (Schön, 1983, p. 79). The same can be seen when designers collaborate and engage in conversation through an object they are designing. While the object remains incomplete, it raises questions that are "begging an answer" (Ewenstein & Whyte, 2009, p. 27), inviting people to refine or complete it, which raises further questions that others may contribute to in an "ongoing and dialogical" (Ewenstein & Whyte, 2009, p. 27) process. In his book entitled "Cognition in the Wild," Hutchins (1995) argues that cultural activity systems have cognitive properties of their own and, by extension, can participate in conversations. Distributed cognition extends thinking beyond an individual mind to groups and objects (Norman, 1991) tied together through social and material connections (Leonardi, 2013; Orlikowski, 2010).

Epistemic objects and sociomateriality

Second, by examining three distinct contexts, we offer much-needed nuance about the characteristics and roles of objects in complex design projects while also validating our results across settings. The three settings differ in the types of clients and projects they work with, as well as the experiences and preferences of their teams. Differences in general approaches were noted, e.g., experimentation in setting 1, analysis in setting 2, ethnography in setting 3, as well as the types of design tools and technologies employed. Nevertheless, across the three settings, the characteristics and roles of objects are similar. The framework developed based on observations in setting 1 was validated and elaborated in the other two settings, giving confidence in the usefulness of the theoretical categories. A great deal of design research draws on single settings and circumstances, leaving the issues of validation and generalization for future research. We take a step towards overcoming such contextual myopia by conducting in-depth research in three distinct settings.

Third, we validate previous research findings and introduce a new theoretical framing. For example, we support and build upon Brereton's (2004) observations about distributed design practice. Nonetheless, we add new nuances that account for newer technologies that have become ubiquitous, such as 3D printing, and offer explanations of why other technologies, such as CAD and VR may be appropriate from a sociomaterial perspective. We also bridge the design and organization literatures to expand the application of sociomateriality, which is rarely applied to studies of design (Matthews et al., 2021). In so doing, we offer a new theoretical lens for explaining what is known about how people design as well as helping to guide appropriate use of objects and effective use of technology in design.

4.2 Limitations and directions for future research

This research investigates design practice from a sociomaterial perspective, drawing together concepts from social and organizational sciences. It contributes to explaining practices that are potentially taken for granted by experienced designers while demonstrating that such practices may not be shared by all members of a design team. This is important in the context of projects that require input from diverse stakeholders and design teams with diverse membership. The research method focused on representing the diverse perspectives of design team members by relying on their first-hand accounts and explanations, supplemented by the researchers' observations and interpretations of the objects they presented. While this approach has precedent in sociomaterial studies (Orlikowski, 2002), focusing on individuals and their words is a limitation. Future research can expand this by combining the approach of studying design "in the wild" (Ball & Christensen, 2018) with a detailed analysis of objects (Stigliani & Ravasi, 2018) as well as representing individual perspectives. Additionally, while the research suggests some characteristics of objects that contribute to their ability to unite or divide diverse teams, these characteristics could be more formally tested. In an increasingly digital world, preferences for physical or digital tools vary. The present research suggests that the most crucial consideration may be whether the objects created by these tools are epistemic objects or technical objects rather than whether they are comprised of pixels or atoms. The results related to the agency of epistemic objects could be further examined to explore how new and old technologies can be combined effectively.

Declaration of competing 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.

Data availability

The authors do not have permission to share data.

Appendix 1. Protocol for Semi-structured Interviews

Questions	*Prompts*
What kind of projects do you work on?	◦ Can you give some examples of typical projects?
What are typically the main stages and how do you move between them?	◦ (E.g. review gates? Is it possible to move back to a previous stage?) ◦ Who does what in a typical project? ◦ How is the communication within teams? Between teams? With managers? With clients etc?
To what extent would you say that the requirements are clear at the beginning of these projects?	◦ Does everyone involved know what the outcome will be? ◦ Does everyone involved agree what the outcome should be?
How is uncertainty over requirements and outcomes managed in projects?	◦ What types of uncertainty are typically experienced? ◦ Who makes decisions? Project managers? Clients? ◦ What decisions can the project team make?
How do you personally deal with uncertainty that arises throughout the project?	◦ What external knowledge would you rely on? ◦ How do you solve problems?
What does *design* involve in this context?	◦ Do you see design as an activity? ◦ Who do you consider to be designing? ◦ What is not design?

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(*continued*)

Questions	*Prompts*
What design "tools" do you use at each stage and how do you use them?	∘ Sketches? ∘ Physical models? ∘ Digital models? ∘ Simulations?
Could you talk about your use of prototypes in design?	∘ How would you define a prototype? ∘ What, if any, prototypes would you use for • Testing concepts? • Communicating concepts? • Form? Function?
Please provide examples of these types of prototypes (images, videos or objects)	For each example, please discuss ∘ Why this mode was chosen? ∘ How it was used? ∘ What the result was? ∘ What the next steps were? ∘ How others (team members, managers, clients) responded? ∘ What, if any, impact there was on the project?
How do you integrate the use of these different prototypes?	∘ Do they serve different purposes? ∘ Are they used in isolation or combined? ∘ What benefits does each offer?
How do you move between digital and physical prototypes?	∘ What do you see as advantages/disadvantages? ∘ How do you use rapid prototyping/3D Printing? ∘ During your education/career, how has technology altered the way you work?
Can you give an example of one project in which you used different forms of prototype?	∘ What did you do? ∘ Why did you choose this type of prototype? ∘ What was the outcome? How did others respond? ∘ What would you do differently?

Appendix 2 Summary of types of objects encountered, purposes (Comi & Whyte, 2017) and representative quotes.

Object	*Purpose*			
	Imagining	*Testing*	*Stabilizing*	*Reifying*
Sketches				
Hand-drawn sketches	Ideas emerge through visual representation and interaction with unexpected emergence, including errors that lead to valuable insights. *"Sometimes you can sketch the wrong thing, but actually just because that line is in a slightly different place. It just clicks something that makes you think. Oh, hang on, instead of being to the left that could go to the right, and that would just be an error in sketching that then makes you even think actually I could do it."* (P)	Sketching forces designers to express their ideas and concepts, thus testing and improving them. *"In your head you think that's the best idea in the world. If you put it on a piece of paper, you think hang on that's never going to fit because you can't get your hand in it."* (A)	A sketch is perhaps the simplest way of representing a design, helping to communicate a concept from the designer's mind. *"I'm talking to you and I want to explain something but I can't explain it very well, I just sketch it down. Maybe a few labels on there and after that I get the point across."* (B)	Important concept selection decisions are often made on the basis of sketches. An idea can become fixed early on, after selection from a set of sketches. *"… I struggle to visualize with words that are written, I like to be able to see … how things are going to fit together and how I can just picture it working. So you down select concepts … ultimately what you want to do is you want to come out with one idea which is your best …"(E)*

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Object	*Purpose*			
	Imagining	*Testing*	*Stabilizing*	*Reifying*
Fabricated models				
'Toy' models	Similar to sketching, the flexibility and speed of assembling construction toys allows emergence of ideas. *"I tend to build in Lego because it's just quick, like super-quick to just change things over, you can try things out and go no, no, that's wrong. You haven't lost any time waiting for parts to be made, I just know, I just swap out bits to just experiment with ideas." (C)*	Building physical representations helps to test specific functional elements of a design. This can be achieved using mechanical construction toys such as Lego and Meccano. *"… for the concepts I used Meccano … without prototyping it, it's difficult to get your head around on paper whether [a concept] is actually going to work or whether it is all going to lock up or whatever, but that proves it. And when you show the customer, there's no argument, it's like: it's there! It works! [laughs]."* (M)	The simplicity of the tools allows mechanisms and moving parts to be quickly created to communicate products or parts of products that may have complex movements. *"we had to come up with a design or some model that would demonstrate it and then we would present that model to the rest of the group, convey our ideas about how this particular product would work … we basically built a Lego model … it's a valve that the idea was, it had this sort of shut-off mechanism so once the fluid entered into a certain chamber you could then basically close off the entry point or exit points or open them if required."* (H)	The mythical status of toys like Lego has created what some feel are unrealistic expectations. The tools themselves are reified, and their limitations may be overlooked. *"you're never going to build what you make out of Lego. Its alright for proving a concept works … you can demonstrate that this is how this product is going to do what we say its going to do, but its still Lego, I can see its got its uses but it is restrictive … there is an assumption that you can come up with something that's an amazing design just based on putting Lego bricks together …"(D)*

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Object	*Purpose*			
	Imagining	*Testing*	*Stabilizing*	*Reifying*
Fabricated models	Using available tools or materials helps to explore ideas and generate working concepts, generating insights through physical interaction with design. *"if you make it [from traditional materials] and try it out, you have to make a big leap of imagination with the object to how you would manufacture it, but it might help you make that creative leap that you wouldn't otherwise get if you, you know, tried to draw it, CAD model it, or analyze it … it's a tactile thing"*. (L)	Moving quickly to a physical representation helps to prove (or disprove) concepts in order to move the design further by reducing unknowns. *"… basically it's a low-cost model that's quite often going to be made from easily and quickly manufactured components or found components or things we have lying around or things we can cobble together for little money to be able to determine whether the idea in a concept is viable."* (L)	Physical representations may not accurately represent the whole product, but communicate elements of the design, for example dimensions, better than sketches or computer models. *"… we can show sketches to the client from now until the end of time and they'll think it looks great but as soon as you put a [representative] 'box' in front of them they go "God that's bloody enormous!" and in fact that's what they did, they went "we really like it, but it looks big." … until you see something next to you, it's difficult to visualise it isn't it?"* (A)	N/A − fabricated models were typically viewed as temporary and evolving objects.

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Object	*Purpose*			
	Imagining	*Testing*	*Stabilizing*	*Reifying*
Digitally fabricated physical models	Digital fabrication makes it easier to move from computer to physical prototype, giving a tactile interaction that helps iterate and develop ideas. *"… one of the big problems with CAD is scale, you know, you model something on screen and then the whole thing is too small and if you print the 3D model out you think it needs to be about 20% bigger and sometimes those things are really difficult to appreciate until you get back out of the digital world … it's just sometimes you only see things from the physical item." (L)*	3D printing and laser cutting, rather than creating whole models, are used in combination with off the shelf or fabricated parts to test concepts. *"… before I went into CAD I went on the shop floor and got where there were lying around bits of metal, cut them up, 3D printed parts, springs, levers and basically just knocked something up that worked, basically just got a working thing and that got transferred into a CAD model." (B)*	Digital fabrication offers a level of accuracy that communicates the design, while allowing for speed and iteration. *"… we modelled it 1 to 1, reduced the scale, printed off some prototypes that reduced size and that gave them a feel. We actually brought it into the meeting and they used a 3D printed part to basically make sure the sizings were correct. Whereas to machine those it would have taken x amount of days whereas that took half an hour."*	Turning a digital model into a physical one makes it seem more real and more convincing to customers and investors. *"we developed a 3D printed version [of a design] so the customer could see physically what it looks like, how the mechanism worked … he wanted something he could take to a conference … so he could sell the idea of it to try to get further funding" (S)*

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Object	*Purpose*			
	Imagining	*Testing*	*Stabilizing*	*Reifying*
Computer-generated models				
Virtual Reality (VR) representation	VR can be used to quickly represent concepts, enabling the kind of interaction that others achieve through sketching. *"I've tended to drift a bit more towards VR and kind of virtual reality, virtual mock-ups and things like that, so much more kind of pre-visualizing the products before they've been made or designed and is often, it's kind of before you've even started on the CAD, we'd create a quick mock-up of what it might look like at the end."* (J)	Early use of VR can be used to test and reject concepts, prior to excessive development costs being invested. *"Usually it is supposed to come in right at the very beginning. So it kind of gives everyone an understanding of where they may be going, you know, so kind of throws out ideas right or wrong that get people thinking about problems [to be addressed in design]"* (J)	VR allows visualisation of information, helping to communicate and consider a broad range of elements that affect the design. *"We do a lot of kind of design reviews where a company will come with a CAD model that they've just finished, before they go and start machining. And we'll actually go in and do a virtual assembly we'll take that CAD model and starting from base components and look at can we actually build this part? Can you get in to repair that component? It's communicating and kind of visualizing data that's already out there. But in a much more human friendly way."* (J)	N/A – VR was used to visualise and evolve process designs, rather than represent a final object.

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Object	*Purpose*			
	Imagining	*Testing*	*Stabilizing*	*Reifying*
Computer Aided Design (CAD) model	CAD is generally felt to be restrictive for idea generation, but nonetheless can be used to facilitate idea generation. *"… there are occasions where you do it right the first time, but usually … there's a few changes that you make in CAD and in your mind, I make all sorts of iterations, I make more iterations in my head than even spoken or written down."* (P)	CAD helps to make concepts more precise, testing the relative scale of components and giving some feedback on how parts interact in a product. *"Often when you sketch something that looks right, when you actually put it in CAD with the actual sizes, it doesn't quite work, which is why I like to, by all means do a lot of sketches to get the concept, but then as soon as I can, go to something like AutoCAD to make sure that things are actually going to fit the way that I think they're going to fit."* (M)	CAD enables rapid modification to help reach agreement on designs, while maintaining a focus on feasibility of manufacture as well as the fit and interaction of parts. *"I just find it's so much quicker [than making physical models]. So if you say I need to scale this up by ten, you can literally click the button two times and make it bigger … and when I design stuff on CAD, I find it easier to visualize how you manufacture it."* (E)	CAD models give an impression of completeness and finality, particularly when rendered to look realistic, but this may be illusory. *"… you look at a really nice shiny fancy CAD model and [you say] 'I want that!' well its not going to look like that because that's a pretty rendered picture. 'Oh but I want that' …" (Y)*

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Object	*Purpose*			
	Imagining	*Testing*	*Stabilizing*	*Reifying*
Computer simulation	Simulation and analysis can generate designs that the latest manufacturing technologies can feasibly produce. *"One of the tools in particular is topology optimization. We're actually looking at allowing the algorithm … to look at the most efficient load path through that particular volume we've given it and ultimately spit out a structure, which is the most efficient use of material. Being able to use that as early as possible has helped with the concept stage."* (O)	Analysis helps to reduce unproductive experimentation, by proving or disproving part of a conceptual design, based on available knowledge. *"If it's going to be a lot of machining, or if you're really uncertain, or its going to cost a lot of money, then we'd have to do some analysis first. Even if it's just very basic just single point load … you'd go down the route of simulation and just double check what you're going to make should work before you commit." (E)*	Simulations can serve to convincingly portray ideas. *"The difficult part is convincing people of the results …. It's convincing the designer, even myself, that what I'm showing somebody is a valid response … most often within a project we don't have the scope for testing"* (O)	The precise and clean nature of a computer simulation gives the impression of finality. *"[some designers are] just not interested in the hands-on aspect [of design, they] would rather sit in front of the computer and do analysis, which didn't invalidate [their] design" (M).*

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