ADAPTING NOVEL RESEARCH TECHNIQUES TO ANALYSE COLLABORATION IN OFFSITE MANUFACTURING HOUSING CONSTRUCTION INNOVATIONS

Zelinna Pablo[1], Kerry London[2] and Peter Wong[3]

[1] *University of South Australia, GPO Box 2471, Adelaide, South Australia 5001, Australia*

[2] *Built Environment and Urban Transformation University of Western Sydney, 169 Macquarie Street, Parramatta NSW 2150 Australia*

[3] *School of Property, Construction and Project Management, RMIT University, La Trobe Street, Melbourne, Victoria 3000 Australia*

The Australian housing sector continues to function in a traditional, inefficient, craft-based manner. A few exemplary supply chains have addressed these challenges through innovative offsite manufacturing (OSM) techniques. Despite its benefits, uptake of OSM in Australia remains limited. A fundamental challenge to OSM is the lack of collaboration across the deeply fragmented housing construction sector. While collaboration is critical in these settings, theoretical work on the topic remains limited. This paper's aim is to examine collaborative practice in innovative housing construction supply chains in Australia using an innovative methodology that supports actor-network theory with causal loop diagrams. Drawing on qualitative data from five OSM supply chains, elements that influence the creation stage of collaborative networks were identified, along with inter-relationships between them. Actor-network theory is applied to initially structure the identified elements into a tentative sequential process. Relationships between elements including their causal influence, feedback loops and polarities are then proposed through a causal loop diagram. The outcome is a model of collaboration in OSM settings that identifies key elements in the critical first phase of network creation to enable innovations in OSM. The model can readily be translated into practitioner materials that build collaborative capacity in the construction industry.

Keywords: actor-network theory, causal loop diagram, qualitative systems dynamics

INTRODUCTION

Housing indicators have historically been robust in Australia (Kitson *et al*., 2015), but alarming trends in the last few decades clearly indicate that the housing sector is under acute stress. Dwellings in Australian cities are among the least affordable in the world (Demographia 2016), compliance levels with environmental standards have been dismal (Pitt and Sherry 2014) and average construction time has lengthened by 40% in less than two decades (Gharaie, Wakefield and Blismas 2010). Many of the current housing challenges can arguably be traced back to the housing construction industry's lack of efficiency and severe fragmentation (Loosemore, Dainty and Lingard 2003). One

[1] zelinna.pablo@unisa.edu.au

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proposed solution to these deep-seated issues is offsite manufacturing (OSM), where parts, components, systems, or entire housing units are manufactured in a controlled environment away from the traditional construction site (London, Khalfan and Pablo 2015). We have examined five OSM housing construction supply chains closely in the course of a three-year national research project. Our research into these OSM networks was based on two premises: that OSM innovation can fuel large-scale industry transformation, and that extraordinary levels of collaboration are needed to drive these OSM innovations. In this paper, we focus on the latter. Specifically, our aims here are to (1) to contribute to developing an enriched theoretical model of collaboration in innovative housing construction supply chains, and (2) to report on our experimentation with a social science methodology that is not widely utilised by construction management researchers. We demonstrate in particular that supporting actor-network theory (ANT) with key elements of causal loop diagrams (CLDs) can provide researchers with a detailed methodological toolkit for generating rich descriptions that capture in fine-grained ways the diverse conditions that influence the creation of innovative housing construction networks, along with the relationships of causal influence that exist between them.

COLLABORATION IN HOUSING CONSTRUCTION

Collaboration is a key strategy for supply chain integration (Simatupang and Sridharan 2005), and has been a subject of considerable interest in the area of construction, where fragmentation is a recurring issue. In most cases, collaboration is a term that is simply mentioned as an activity or practice (Mao *et al*., 2015) or implied in discussions that foreground supply chain integration (Kim, Kim and Cho 2015). In other cases, researchers have attempted to propose brief definitions of the term (Isatto, Azambuja and Formoso 2013). In a very limited number of construction studies, researchers have begun to explore collaboration in systematic ways (Walker and Walker 2015), however this pool of research remains surprisingly underdeveloped. In a broader multi-disciplinary review of collaboration literature, we have found there is deeper theoretical development, but much of the work on collaboration is still grounded on a narrow and limiting set of assumptions that fails to consider important characteristics of the construction industry (London and Pablo, in press). Yet collaboration in construction is an area that warrants attention, given that housing construction projects involve high levels of interdependence among actors. In such cases, collaboration has been described as “the only viable response” (Gray 1985: 916). We argue that using a network approach, specifically actor-network theory, can enrich theoretical conceptualizations of collaboration in ways that are appropriate for construction settings.

USING ANT SUPPORTED BY CLD

Actor-Network Theory

Actor-network theory is an analytical approach that assumes that much of reality is the outcome of human and non-human actors interacting in heterogeneous networks (Callon 1999, Latour 2005, Law 1992). Networks develop through a complex, non-linear process called translation. Translation begins when a prime mover seeks to create a network by *enrolling* different actors. These initially disparate actors begin to *converge* and function as a single unit; the programs and goals of the network then *stabilize* into routines; then the network *expands* across time and space (Callon 1999). Each stage of ANT can be further broken down. Network creation, for example, involves a prime mover framing a problem and a solution to be addressed (problematization), defining the attributes of actors needed to address it, along with their potential roles (interdefinition of actors), employing strategies to convince actors to take part in the network on the grounds that it is the only way that they can achieve their own goals (obligatory points of passage), cutting actors away from competing roles and identities (*interessement*), and convincing at least some of these actors to become part of the network (enrolment) (Callon 1999).

We have in other work used the ANT concepts above to expand existing understandings of collaboration in construction. ANT concepts such as general symmetry, multiplicity, and convergence, for example, can lead to an understanding of collaboration that encompasses humans and non-humans, layers of overlapping networks, and complex notions of coherence instead of conformity (London and Pablo, in press). The strengths of ANT as an analytical approach rest in part on its commitment to detailed empiricism. ANT researchers are expected to commit to the "careful tracing and recording of heterogeneous relational networks" (Doolin and Lowe 2002: 76). To achieve this, researchers seek to formulate rich descriptions of actors and of associations between them. Ideally a description is developed to the point of saturation, that is, descriptions of elements within the network are so exhaustive that there is no need for additional descriptions from outside the network. At this point, descriptions and explanations become one and the same (Latour 1991). This ANT ideal is sound, yet implementing it raises methodological difficulties. Ponti (2012) points to a key challenge: while ANT commits deeply to detailed empiricism, it does not prescribe any one data analysis technique for achieving this. Ponti (2012) thus proposed that this gap could be addressed by combining ANT with a tool known as event structure analysis. We take up a similar argument, arguing that ANT researchers can benefit by supporting the use of ANT with another specific tool, in this case systems dynamics and causal loop diagrams.

Systems Dynamics, Causal Loop Diagrams, and Possible Links to ANT

The term "systems dynamics" refers to a method that seeks understand, model and learn from the dynamic complexity of human and social systems in ways that allow people to address multifaceted problems. The process of modelling a dynamically complex system begins with identifying a problem, then expressing it in terms of an initial set of variables progressively expanded through an iterative mapping process that seeks to explicate cognitive models. A map can be devised using various tools; the tool we use here is the causal loop diagram. Causal loop diagrams (CLDs) are made up of three components: variables, links between variables meant to suggest causal influences, and polarities of links (positive or negative). Several components can be linked together in a loop (Sterman 2000).

While CLDs have historically been understood as a quantitative analysis tool, we propose here that it is a tool that can support ANT, an approach underpinned by dominantly non-realist, qualitative assumptions. To justify this we make three points. First, CLDs can be mobilized in quantitative as well as qualitative ways and quantitative mobilizations, while dominant, are not always "better." For example, researchers have found that traditional CLD modelling requiring full quantification of variables and links is, in many cases, an unrealistic goal. The extra effort required to achieve this may also not be value-adding, particularly when complex efforts of quantification are founded on multiple uncertainties and questionable assumptions (Wolstenholme 1985). Thus our second point: qualitative CLDs, initially seen as pathways to quantitative models, are increasingly seen as valuable in themselves. Qualitative models represent complex problems in succinct ways, enrich understandings of problem contexts and guide discussions and agendas (Coyle 2000). In this case, we argue specifically that CLDs allow ANT researchers to discern causal chains in studied phenomena, in ways that allow ANT researchers to "write rich descriptions that 'show' fluid associations among things, revealing what gives actors the energy necessary to act" (Ponti 2012: 2). When the underpinning associations in a collaborative network are causal in nature, CLDs can capture these in vivid ways. This leads to our third point. In such an undertaking, analysis hinges on what is meant by "causal". In this study, we align ourselves with qualitative mobilizations of CLDs, thus we necessarily move away from positivist accounts of causality where events A and B are linked by law-like relationships that can be expressed in a mathematical formula or graph. In ANT generally and in this study specifically, causality is assumed to be underpinned by the idea of multiple determination: events are "caused by the interaction of multiple causal powers", potentially "frustrated by the operation of conflicting powers" and are without "guarantee of empirical regularity" (Elder-Vass 2015: 13). This notion of causality, we argue, can still be captured by CLDs, but to do so we must revisit CLD building blocks (the variable, the link, and the polarity), which tend to be understood from mainly positivist positions. We do this in the methodology section. In summary, then, we are mobilizing CLDs to create a qualitative model that reveals chains of causality in a way that explains the conditions leading to the creation of a collaborative network, thus supporting the ANT goal of developing a detailed description/ explanation of associations between actors in a studied phenomenon.

METHODOLOGY

We develop a model using ANT and CLDs based on findings from our three-year national research project that examines five Australian-based networks that have embarked on innovative offsite manufacturing initiatives. These networks were led by organizations acting as prime movers, and these organizations were selected to achieve maximum variation (Flyvbjerg 2006). Specifically, these lead organizations varied in size (one micro, three small/ medium enterprises, one multinational), maturity (two start-ups, two in the growth stage, one mature), level of OSM, and purposes for moving into OSM. Data was gathered primarily through 29 semi-structured interviews, but we also visited sites and viewed videos of OSM operations. Interview questions were intentionally framed in a broad way, with initial questions focusing on human and non-human actors, drivers and barriers to OSM, as well as drivers and barriers to collaboration in OSM projects. Human actors were identified based on actors' meaningful involvement in an OSM project. Non-human actors were identified first through frequency of references to them, for example participants mentioning equipment, funding, factories, and drawings as critical to the network. Their significance was further validated through our observations during site visits, as well as through analyses of videos and photographs. Data was analysed using NVivo, and a thematic analysis of data from across these cases yielded 102 different themes. To give some very brief examples: questions on drivers to OSM yielded themes such as increases in speed, customization, and worker health and safety; drivers of collaboration included themes such as positive attitudes towards change and the presence of a strong champion.

While our initial analysis yielded a detailed list of themes, they were not, at least initially, linked in any meaningful way. To being this "linking" process we used the idea of translation as an organizing device for initially discerning more straightforward relationships of sequentiality (Pablo and London 2017). Translation, as we mentioned, can be divided into stages (Callon 1999), but other researchers suggest there are other more finely-tuned ways to break it down. Pentland and Feldman (2007) and Ponti (2012), for example, propose that translation can be broken down more minutely using events as a unit of analysis. An event involves at least two actors and an action that takes place between them ("Company X uses funding to buy equipment"). Events contribute to the advancing of a narrative or story, and can be sequentially ordered around the question "What happens next?" as a network unfolds. While Pentland and Feldman (2007) deliberately focused on events that were fleeting in duration, they also noted the importance of routinized patterns (extended events) in organizational life.

In this study we move from seeking relationships of sequentiality to relationships of causality. We thus propose here that a viable unit of analysis is something similar to Pentland and Feldman's (2007) routines, and we refer to this unit as the "condition". A condition in this study has three characteristics. First, it involves actors and actions that are linked in sustained, repeatable, recognizable patterns. Second, a condition *tends to influence* other conditions, but again, in line with our tempered definition of causality, this is a general tendency not guaranteed to have empirical regularity (Elder-Vass 2015) and does not require unilateral determination. Third, a condition can be described as "increasing" or "decreasing", but in ways that reflect general direction, not precise mathematical formulae. To reflect these characteristics, then, a first step we took was to reframe our themes to reflect these. For example, a theme originally framed as "Presence of a champion" is now called "Commitment of champion to OSM solution". Once "conditions" were in place, we were prepared to analyze possible causal relations between them.

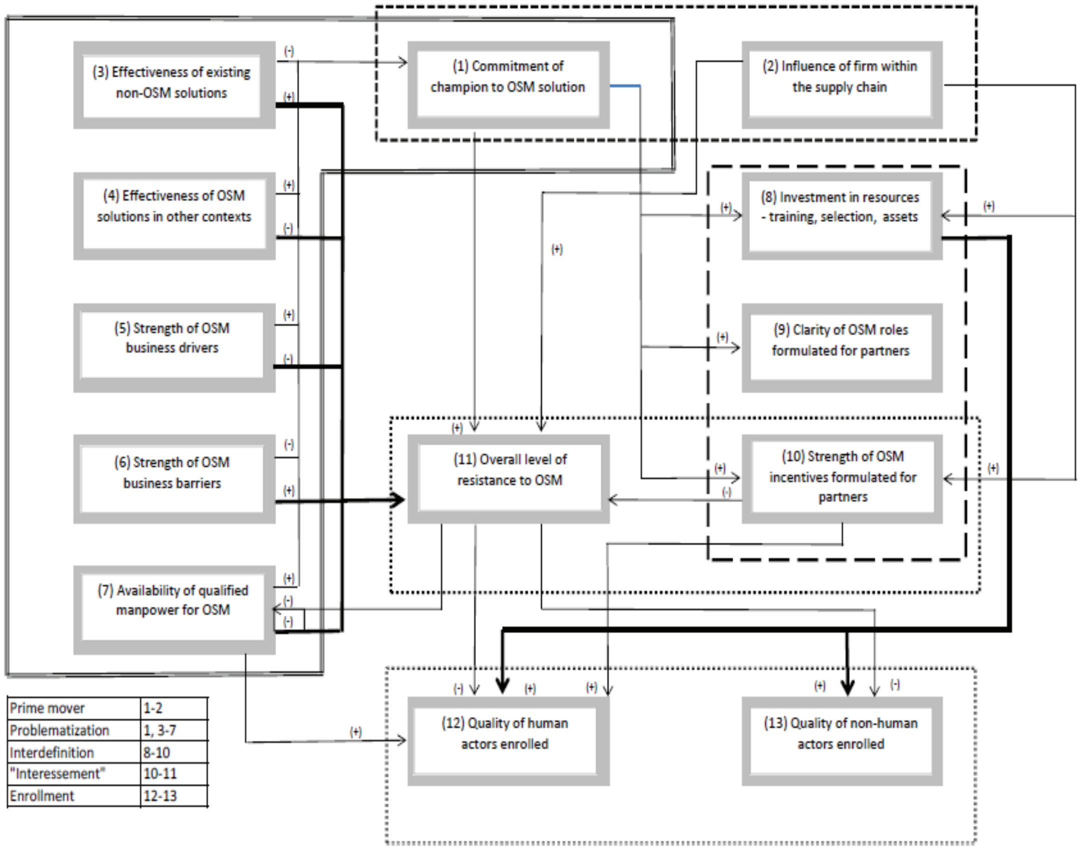
FINDINGS AND DISCUSSION

Having clarified the conventions we used for building qualitative CLDs (defining causality, renaming themes), we then sought to identify the chains of causal conditions leading to the creation of a collaborative OSM network. Our initial analysis of arranging conditions based on sequentiality (Pablo and London 2017) was thus fine-tuned, moving away from the question "What happened first/ next?" to asking "Does a change in Condition A *tend to influence and change* Condition B?" A similar question guides event structure analysis (Ponti 2012), but we have modified the question to accommodate the definition of causality we discussed earlier. Initial responses were formulated by the research team based on participant narratives. Causality in participant statements could be discerned in various ways, for example in accounts like "Project Leader X was very positive about OSM" [therefore] "we all got on board". Links between conditions proposed by the research team were then presented to industry partners for feedback. Based on our five case studies, we propose that there are 13 causally-linked conditions leading to network creation (see Figure 1).

Figure 1 was based on findings from all five case studies. Due to space limitations, however, our explanation of how we arrived at it is limited in this paper to discussions of two contrasting case studies. Case Study 1 involves a multinational firm that has moved from purely traditional building to incorporate innovative OSM techniques. It has successfully created a collaborative network that now makes use of prefabricated cassette floors. Case Study 2 involves a start-up that sought the acquisition of disruptive European technology to prefabricate wall, roof, and floor elements for bespoke houses. It ultimately failed to create a network. We present the different conditions for network creation, along with detailed supporting data from both case studies to illustrate each condition, in Table 1. The causal links between conditions are further explained in narratives below. Embedded in the narrative are symbols like "3→1", which means Condition 3 tends to influence Condition 1. For the sake of brevity our narratives focus on selected links between conditions. That said, the links that we do not explain can nevertheless be inferred from the complete Figure 1, particularly after we walk readers through narratives.

In Case Study 1, the conditions for successful network creation can be explained as follows. Ineffective construction solutions led a champion to commit to OSM, based mainly on concerns about worker safety (3→1). The champion sought to enrol OSM actors with a specific emphasis on seeking the best people through stringent selection (1→8).

Figure 1: Proposed causal loop diagram of network creation.



The success of this process was buttressed by the company's strong track record for innovative building methodologies (2→8). While existing networks like partner, regulatory and financial networks were still be programmed to run along traditional building practices leading to resistance (6→11), the influential position of the organization, bolstered by its track record, tempered this resistance, thus conservative supply chains and regulatory networks were over time made "ready" and accepting of the change (2→11). The enrolment of human actors proceeded in a relatively unimpeded manner not only because of focused recruitment/ selection efforts (8→12) and because overall resistance to OSM had been addressed (11→12). Non-human actors like equipment were recruited unproblematically because of intentional efforts to invest in OSM resources (8→13), and because potential resistance in key networks (for example banks) had been addressed (11→13).

Network creation took a different and largely unsuccessful route in Case Study 2. The champion's commitment to OSM was also strong, grounded in issues linked to quality and precision (3→1). The champion sought to enrol best people through planning efforts that would position his firm as the employer of choice (1→8). However, the potency of efforts to enrol OSM assets was diminished because the company was new and lacked a track record of successful projects (2→8).

Partner networks were also resistant as in Case Study 1 (6→11), but unlike in the previous case, the new, fledgling company was in no position to champion this change (6→11). The enrolment of human actors, while buttressed by promises by the company to uphold innovative human resource practices (8→12) was met with limited success, with overall sentiments of scepticism remaining and very few actors finally entering into limited "soft" agreements to participate in the future (11→12). Such future participation was also contingent upon the acquisition of new equipment, but resistance from banks has prevented this (11→13). As of this writing, network creation continues to flounder; the "champion" that had led many efforts has now left.

Table 1. Causal conditions for network creation

Conditions	Case Study 1	Case Study 2
Effectiveness of existing non-OSM solutions (3)	WEAK. Existing solutions require manual building at heights. Lead company and key managers were led to ask questions: "how do we build even faster again and do it even safer? How do we keep all the guys off those top floors?"	WEAK. Existing non-OSM solutions tend to be slow and imprecise. Lead company concludes: "…taking nothing away from what builders are doing, they're never going to be as accurate as what our machines are…So, at the end of the day what we're producing is going to be of high quality but done a lot quicker."
Commitment of champion to OSM (1)	STRONG. Leaders thus looked to OSM. They "were very positive and they were looking at ways of, let's have the attitude of what can we do to make it work, and not find ways of not making it work."	STRONG. Leaders looked to OSM. "A Melbourne based company, really passionate about the creation of jobs…saw [OSM] and said 'yes, I like this.' And then came back and did some economic studies around the whole process and around the industry changing."
Influence of firm within the supply chain (2)	INFLUENCE ON SUPPLY CHAIN STRONG BASED ON PAST SUCCESSFUL EXPERIENCE. Leaders then sought to champion OSM across the supply chain gradually: "…we've been out there spruiking what we've done over the last couple of years with industry, with the organisations such as FWPA, Timber Australia… we're not afraid to give the information out there so that people can come along and say, look, this can be done by other parties as well at the end of the day."	INFLUENCE EMERGING BUT MOSTLY SPECULATIVE, BASED ON FUTURE EXPECTATIONS. Leaders sought to champion OSM: "[We] worked with the City A and City B Councils on putting some papers together and they did some studies and the economic climate of jobs and positions for the west, right through that whole region. And the automotive fund and all that side of it."
Strength of OSM business barriers, for example	WEAK. Because of the championing efforts over time, OSM solutions were not seen as radical departures and could be accommodated under existing regulations. "Because it had to be an	STRONG. Despite championing efforts, the lead firm's OSM solutions were seen as new and could not be accommodated under existing regulations. "The business case stacks up and that's what they like

Conditions	Case Study 1	Case Study 2
regulatory barriers (6)	alternative solution to our current building codes so we had to take the building surveyors through a whole journey to say, yes, this is equivalent to a concrete building from a fire perspective, from an acoustic perspective, from a longevity perspective."	about it. So it's now convincing them to say okay - it's actually there, everything's in place. But banks are all scared because of your 9/11 and all that good stuff that happened way back. They're not taking that risk anymore."
Investment in resources training, selection, assets (8)	HIGH PRIORITY PLACED ON FINDING THE RIGHT PEOPLE. To get started on OSM, lead firm decided to pursue only the "best" people: "…we will use the connections that we have around the table that we have right now. So I would go to Company X and say, I'm about to go WA [Western Australia]. Who are the best and most capable frame and truss manufacturer in WA?... So it's word of mouth, it's reputation and we will go and obviously assess that supplier ourselves."	HIGH PRIORITY PLACED ON FINDING THE RIGHT PEOPLE. To get started on OSM, lead firm decided to position itself as "the" preferred employer: "It's all around about setting up people around the community of what people would bring on board. What's the training skill? What's the employer of choice meant to be like? So we've done a lot of that planning upfront, really saying what is the business going to look like?"
Overall resistance of the supply chain (11)	LOW LEVELS OF RESISTANCE. Lead firm and key managers presented OSM as something new, but nevertheless "I keep telling everyone that the technology is there, the supply chain is there." Partners, though daunted by the newness, responded positively to the lead firm's confidence by saying "saying "Yes of course we can do it", [but then] "had to go away and work out how to do it."	HIGH LEVELS OF RESISTANCE. Lead firm and key managers presented OSM as something new: "…we start from ground zero…so forget all the rules that were put in place - - - and come and rebuild the rules with us." Partners remained intimidated by the level of change: "And I think… the automotive guys …we've spoken to and different other guys - they're (sic) going to be hard to transition their mindset."
Quality of human actors enrolled (12)	SUCCESSFUL ENROLMENT OF COMPLETE TEAM OF QUALIFIED HUMAN ACTORS. "So we went out to the largest frame and truss manufacturers who had the best detailers in their, I guess, pool of employees. We went to a flooring company who had the ability and cashed up to be able to do all the independent testings that we wanted to be done. And we had the best engineers on board."	TENUOUS ENROLMENT OF SMALL TEAM OF HUMAN ACTORS, RECRUITED BASED ON FAMILIAL TIES. "So we've soft saved quite a few people that we want to bring on board…when we've got our financing resorted then we'll start the on-boarding process, but we have probably five people at the moment that are fully dedicated, full-time… most of them are from my family…"
Quality of non-human actors enrolled (13)	SUCCESSFUL ENROLMENT OF CRITICAL NON-HUMAN ACTOR/ EQUIPMENT. "(Partner Company X has also) gone and actually bought and spent a couple of million dollars buying equipment …Now, that puts them in a fairly unique position. because that means if someone wants to compete with it they've got to go and invest in this equipment…"	UNABLE TO RECRUIT NON-HUMAN ACTOR/ EQUIPMENT. "…there's probably two major things that prevents the banks from funding the equipment and one is that they don't understand it and its specialised equipment, it's new to the market, they don't know what the resale value is..."

CONCLUSION

The main contribution we have made is to implement CLDs qualitatively, in pragmatic ways that support the ANT goal of developing descriptions/ explanations of associations between actors in a network. We have explained how the qualitative mobilization of CLDs using the notion of conditions, along with an understanding of causality built on multiple determination, can be compatible with the qualitative assumptions of ANT. As a result of using this novel methodology, we made a second contribution: a detailed conceptual understanding of what is involved in OSM collaboration at the network creation stage.

Figure 1 thus provides a multifaceted response and a detailed explanation to the question "What are the conditions that influence the successful creation of a collaborative network of quality human and non-human actors for innovative OSM initiatives?" The detailed causal chains in Figure 1 can, in future work, become the basis for detailed narratives which, being endowed with significant interpretative flexibility, can be used as the basis for developing a wide range of practitioner material. In our study, we have begun to use Figure 1 for the development of training materials to develop collaborative capacity in the industry. That said, this study also has a few key limitations. First, our findings were limited to discussing network creation. This is not because it is the only important stage, or even for that matter a clearly and separate ANT stage, but because of space limitations. Second, we are not making the broad claim that the use of CLDs and ANT are always epistemologically compatible. Positivist mobilizations of CLDs may not be compatible with ANT, but because this study uses CLDs in non-positivist ways, it is beyond the scope of this study to work out if such a reconciliation is possible.

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