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ARTICLE

Interdisciplinary teamwork artefacts and practices: a typology for promoting successful teamwork in engineering education

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ABSTRACT
Professional organisations and engineering educators in Australia recognise that interdisciplinary teamwork skills are increasingly important for engineering graduates to develop. However, knowledge and resources for how best to develop those skills is underdeveloped. This article addresses that gap by introducing a new conceptual framework and typology for promoting successful interdisciplinary teamwork. The analysis is based upon several long-term ethnographic studies of interdisciplinary student teams. The conceptual framework is called Interdisciplinary Teamwork Artefacts and Practices (ITAP), and the six types of ITAPs are: (1) orienting, (2) operating, (3) levelling, (4) proposing, (5) aligning, and (6) structuring. This typology can be used to help instructors and students alike navigate the challenges of interdisciplinary teamwork while maximising interdisciplinary learning outcomes.

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Interdisciplinary; teamwork; artefacts; ethnography; shared mental model

1. Introduction

Communication and collaboration are key components of engineering work (Trevelyan 2014), and teamwork, including interdisciplinary teamwork, is increasingly seen as an important component of engineering education programmes (Borrego et al. 2013; Hadgraft and Kolmos 2020; Male, Bush, and Chapman 2010, 2011; Paretti, Cross, and Matusovich 2014).[1] Accreditation bodies consider the ability to both lead and function on teams as an important outcome for engineering graduates (Engineers Australia 2017). Engineers Australia recognises that engineers increasingly 'need to be able to work in cross-disciplinary teams to solve problems and pursue opportunities' (Engineers Australia 2019), and cross-disciplinary skills are needed to address the new challenges engineers face in their learning and work (Hadgraft and Kolmos 2020).

However, 'despite the clear emphasis on teamwork in engineering and the increasing use of student team projects, our understanding of how best to cultivate and assess these learning outcomes in engineering students is sorely underdeveloped (McGourty et al. 2002; Shuman, Besterfield-Sacre, and McGourty 2005)' (Borrego et al. 2013, 473). In order to contribute to current conversations on interdisciplinary teamwork in engineering education, and to advance understandings of how to cultivate interdisciplinary teamwork learning outcomes, this article introduces a typology of *interdisciplinary teamwork artefacts and practices* as a framework for facilitating successful interdisciplinary teamwork.[2] The typology was developed based on data from long-term ethnographic observations across multiple projects in the United States. The overarching research question was, 'Which practices and artefacts are essential for successful interdisciplinary teamwork in engineering education contexts?' Because no such typology exists, this article fills an important gap in both research on interdisciplinary engineering teamwork and pedagogical resources for educators.

The article begins with a literature review that summarises the most salient teamwork concepts identified in prior literature, explains one of those concepts – share mental models – in greater depth, and introduces the concept of boundary negotiating artefacts. The Methods section then presents a methodological rationale for using ethnographic methods in this study, describes the participants and data collection methods that informed the typology, and explains how the typology was created. Next, the typology is presented with empirical examples of their importance provided. The article concludes by elaborating on uses of the typology and its applicability to all student teams.

2. Literature review

2.1. Concepts for successful teamwork

Previously, a systematic literature review identified five key concepts salient for successful engineering education teamwork (Borrego et al. 2013).[3] The concepts were: (1) social loafing, (2) interdependence, (3) conflict, (4) trust, and (5) shared mental models. As summarised in Table 1, this article focuses on concepts 2–5.[4] Shared mental models are discussed in their own

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Table 1. Key teamwork concepts from prior literature*.

Concept	Definition
Interdependence (promoted)	Level of reliance on others necessary to complete one's work
Conflict (minimised)	'Perceived incompatibilities or discrepant views among' team members
Trust (promoted)	Confidence in others; 'faith in trustworthy intentions of others'
Shared mental models (promoted)	'Shared knowledge structures that enable a team to form accurate explanations and expectations', coordinate actions, and adapt behaviours

*Borrego et al. 2013, 488.

section below as they may be less understood than the first three concepts.

Examples of pedagogical strategies for promoting interdependence, trust and SMM, and minimising conflict can be found in Borrego et al. (2013). In this article, these concepts are considered in the context of interdisciplinary teamwork specifically and inform how 'successful interdisciplinary teamwork' is defined.

2.2. Shared mental models

Shared mental models (SMM) – also sometimes referred to as *team mental models* – are, most simply, knowledge structures that are shared by members of a team. SMMs include shared knowledge about the team's job or task, team member interactions, and team composition (Mathieu et al. 2000). Components of SMMs include (but are not limited to) correct understanding of team members' knowledge, skills and attitudes; team members' roles, responsibilities, role interdependencies; and the team's information sources, communication channels, task procedures, and task component relationships (Mathieu et al. 2000). More specifically, Cannon-Bowers, Salas, and Converse (1993) proposed that a team is most likely to be effective if team members share four mental models. The *equipment model* comprises team members' shared understanding of the technology and equipment with which they carry out their team tasks. The *task model* comprises team members' perceptions and understanding of team procedures, strategies, task contingencies, and environmental conditions. The *team interaction model* comprises team members' understanding of team members' responsibilities, norms, and interaction patterns. And the *team model* comprises team members' understanding of others' knowledge, skills, attitudes, strengths, and weaknesses. Having such shared knowledge, enables a team to plan, coordinate their actions, form accurate expectations and explanations of the task and of team members' behaviours, and to adapt their behaviours accordingly – all of which leads to better team performance (Cannon-Bowers, Salas, and Converse 1993; Edwards et al. 2006; Langan-Fox, Anglim, and Wilson 2004; Kozlowski and Ilgen 2006; Mathieu et al. 2000, 2005). The relationship between a SMM and team performance has been documented in the context of engineering student team projects specifically (Bierhals et al. 2007; Lee and Johnson 2008).

2.3. Boundary negotiating artefacts

In addition to those four concepts for successful teamwork, interdisciplinary teamwork requires additional considerations. Because disciplines have their own values, perspectives, assumptions, epistemologies, methodologies and norms, the boundaries between their cultures must be navigated in order to reach common ground (Beddoes and Borrego 2014). One of the means that interdisciplinary teams use to reach that common ground is *boundary negotiating artefacts* (BNAs). BNAs are 'artifacts and surrounding practices to iteratively coordinate perspectives and to bring disparate communities of practice into alignment, often temporarily, to solve specific design problems that are part of a larger design project' (Lee 2007, 318). Lee (2007) identified five types of BNAs: self-explanation, inclusion, compilation, structuring and borrowed. BNAs can take the form of sketches, prototypes, tables, concept maps, models and narratives, among many other forms. For a more in-depth review of boundary negotiating artefacts in the context of engineering education, see Beddoes, Borrego, and Jesiek (2011) and Beddoes and Nicewonger (2019b).

While engineering education researchers have not yet paid much attention to the creation and use of artefacts in student teams, in the field of Science and Technology Studies there is a long tradition of studying the ways in which artefacts are an integral part of science and engineering work (Beddoes, Borrego, and Jesiek 2011). Collaborative engineering work relies on artefacts for recording and transmitting information, and having an object that everyone can refer back to. As Vinck (2011) has demonstrated:

> Studying the objects involved in engineering collaborations reveals facets of engineering work that otherwise remain unseen and are not revealed through either normative descriptions of engineering work or through interviews alone.[13] Studying such objects and following their circulation among collaborators helps identify and categorize key features of engineering design practices that are otherwise unseen … [13] Even though … such objects might appear unimportant, marginal, or overly formalized

> aspects of engineering practices, they are actually an integral and revealing aspect of engineering work, the subject of lively discussions, and take up much of engineers' time. [13] (Beddoes, Borrego, and Jesiek 2011, 2–3)

Focusing on practices alone misses key parts of how engineering work is accomplished.

3. Methods

3.1. Methodology: ethnography

Ethnographic research is designed to produce rich, deep understandings about a particular group or context through the use of long-term, in-depth observations, often combined with in-situ interviews (Case and Light 2011; Fetterman 2010). Compared to survey-based, interview-based, and assessment-based studies, however, long-term ethnographic observation remains relatively under-utilised in engineering education research. That is unfortunate because ethnography can have methodological benefits over interviews and surveys when trying to understand social dynamics, group processes and taken-for-granted aspects of practice. One benefit is that the ethnographer can observe dynamics, processes and practices that may routinely escape participants' own conscious awareness. In other words, in order for a participant to provide information in an interview, they must be cognisant of the desired information to report it; however, participants may take things for granted and not be aware enough of their significance or nuances to report them (Patton 2002). Through observations, an ethnographer can move beyond the 'selective perceptions of others' (Patton 1990, 204). Additionally, the ethnographer can learn about things that participants might not want to talk about in interviews, even if they are aware of them (Patton 2002). Yet another benefit is that the ethnographer can learn about what actually happens, rather than what participants' say happens, which are not always matching accounts (Vinck 2011).

3.2. Data collection and participants

The typology presented in this article was informed by two ethnographic studies. Project A (NSF EEC#1929726), involved twelve months of fieldwork among students and faculty at a large research university in the United States. The team was competing in an international design competition that required designing and building environmentally-friendly tiny homes. Undergraduate and postgraduate students and staff/faculty from multiple disciplines comprised the team, with architecture, computer science, and mechanical engineering being the most observed for Project A. The reasons for student participation differed from student to student and discipline to discipline: the mechanical engineering students participated as part of their required capstone design course; while others volunteered for the experience, and some were paid for their work.

Project B (NSF EEC#0643107) involved two separate fieldwork periods of four consecutive weeks each at two different large research universities in the United States. The two teams were comprised of postgraduate students from multiple disciplines, including biomedical engineering, media arts and sciences, computer science, wildlife sciences and sociology, among others, who were working together for their dissertation projects as part of a national interdisciplinary graduate education initiative.

In both Project A and Project B, the primary method of data collection involved participant-observation (Fetterman 2010) of student and instructor interactions. These observations took place during an orientation retreat, team meetings, lab and studio research and design time, off-campus research sites, and in classes. Individual interviews were also conducted with students and staff/faculty members, during which they were asked about their experiences, perceptions, and knowledge of their interdisciplinary project. Lastly, digital and physical artefacts created by the teams were collected and documented and used as data. Further details about data collection methods, participants and findings can be found in (Beddoes and Borrego 2011, 2014; Beddoes, Borrego, and Jesiek 2011; Beddoes and Nicewonger 2019a).

3.3. How the typology was created

The goal of this analysis was to synthesise and extend findings from the ethnographic studies into a typology of artefacts and associated practices that are salient for promoting successful interdisciplinary teamwork in engineering education contexts. *Successful interdisciplinary teamwork* is defined here as that which fully addresses the four teamwork concepts and maximises interdisciplinary learning; i.e. it promotes all aspects of a shared mental model (equipment, task, team interaction, and team), interdependence, trust and interdisciplinary learning while minimising conflict.

Taking Lee's (2007) BNA typology as a starting point, the first question that guided analysis was, 'Which of Lee's BNAs are salient for promoting successful interdisciplinary teamwork?' Three types of BNAs were identified as salient for engineering student teams (Beddoes and Nicewonger 2019a).

The second question was, 'Do the salient BNAs from Lee's typology adequately account for the full range of artefacts and associated practices that are needed to promote successful interdisciplinary teamwork, and, if not, what other types of artefacts and associated practices are needed?' Through the analysis, it became evident that the original conceptualisation of BNAs was not sufficient for promoting all aspects of successful interdisciplinary teamwork. (Recall that Lee's original typology was descriptive and about a real-world design team in a museum setting; it was not a normative typology created for engineering education contexts.) Therefore, the data was reviewed to determine what other types of artefacts were needed. Salience was determined both by artefacts' presence as well as absence. Identifying the biggest challenges and conflicts teams experienced revealed *needs* that subsequently became types of artefacts in the new typology.

The result was a new conceptual framework called *Interdisciplinary Teamwork Artefacts and Practices* (ITAPs), and a typology of six ITAPs salient for successful interdisciplinary teamwork in engineering education contexts. ITAPs are defined as *artefacts, and associated practices, team members should create in order to maximise successful interdisciplinary teamwork*. ITAPs meet the following criteria: (1) they address the most significant interdisciplinary challenges experienced by the teams; (2) they address the four key teamwork concepts identified in the literature review (interdependence, trust, shared mental model and conflict); and (3) they promote interdisciplinary learning outcomes.

4. Results and discussion: a typology of interdisciplinary teamwork artefacts and practices

This section presents the typology of Interdisciplinary Teamwork Artefacts and Practices that was created as a result of the work described above. This typology delineates types, or categories, of artefacts and associated practices; it does not specify forms. The types of artefacts are form-independent. In other words, depending on the particular context of a project, the forms of artefacts will necessarily vary for each type. Table 2 summarises the types of ITAPs and their relationship to successful interdisciplinary teamwork.

1. Orienting Artefacts: The purpose of orienting artefacts is to familiarise team members with other team members' knowledge, skills, attitudes and preferences. As noted, understanding team members' knowledge, skills, attitudes and preferences is one component of a shared mental model. In the context of interdisciplinary teams, this means learning not only about individuals, but also about team members' disciplinary norms, methods, and epistemologies. Establishing common ground in this way is important because:

> Disciplines have their own unique 'cultures' comprised of values, perspectives, assumptions, epistemologies, methodologies, languages, and norms of argumentation, explanation, and data (Bauer 1990; Becher and Trowler 2001; Bromme 2000; Golde and Gallagher 1999; Gooch 2005; Graham 1999; Journet 1993; Reich and Reich 2006; Rogers, Scaife, and Rizzo 2005). Interdisciplinary research teams must grapple with these differing facets of team members' backgrounds and reconcile the cultures of members' disciplines in order to be successful. (Beddoes and Borrego 2014, 237–238)

Orienting artefacts should serve to develop that component of a shared mental model.

One of the teams in Project B devoted significant effort to systematically cultivate this component of a SMM, and the result was that that team demonstrated the highest levels of understanding other team members' knowledge, skills, preferences and disciplines. Instructors for that team arranged a 'two-day, team-based orientation for all incoming students every year. Students learned about interdisciplinary epistemologies and participated in team activities that familiarised them with

Table 2. ITAPs typology.

Type	Description	Affordances
Orienting	Familiarise members with teammates' knowledge, skills, attitudes & preferences	• Promote SMM • Promote id♦ learning
Operating	Establish shared understanding of how team will operate/function	• Promote SMM • Promote trust • Reduce conflict
Levelling	Prevent disciplinary capture	• Promote id learning • Promote effective interdependence • Reduce conflict
Proposing*	Propose new ideas, concepts, or forms to team members	• Promote SMM • Promote id learning • Reduce conflict
Aligning*	Create alignment and coordination between the team members to produce shared understanding of a problem or to share important design information	• Promote SMM • Promote trust • Reduce conflict
Structuring*	Communicate a guiding vision for the project; establish ordering principles: direct and coordinate team members' tasks	• Promote SMM • Promote effective interdependence • Promote trust • Reduce conflict

*Adapted from Lee's (2007) BNA typology
♦ id = interdisciplinary.

their teammates' disciplines and research interests' (Beddoes and Borrego 2014, 246). These orientation activities, which included creation of orienting artefacts, 'directly facilitated development of SMM by familiarising students with who was on their team, why they were on their team, what disciplinary beliefs they brought with them vis-à-vis research, and how the interdisciplinary theme was related to all teammates' disciplines' (Beddoes and Borrego 2014, 249). On the other hand, in the teams where formal orientation activities and artefacts were not utilised, there was evidence of less interdisciplinary learning and less understanding of teammates' knowledge, skills, attitudes and preferences (Beddoes and Borrego 2014; Beddoes and Nicewonger 2019a).

Therefore, it is worth taking time at the start of a project to facilitate orienting artefacts and practices because the SMM components they develop will pay off over the course of the project. An example of an orienting artefact would be a conceptual model of the research question or design problem that each team member creates and then compares to others' conceptual models. Successful use of such conceptual models is described in Heemskerk, Wilson, and Pavao-Zuckerman (2003). Further resources for facilitating similar orientation activities are available from the Toolbox Dialogue Initiative (2020).

2. Operating Artefacts: The purpose of operating artefacts is to establish shared understanding of how the team will operate or function, in other words, their work practices, SOPs, and logistics. Operating artefacts should ensure that there is a shared understanding of key components of a shared mental model including: task procedures, task strategies, likely scenarios, task component relationships, roles and responsibilities, role interdependencies, information sources and flow, interaction patterns, and communication channels. Having such shared understandings in place from the beginning will reduce conflict throughout the project because it decreases the likelihood that there will be team members operating with opposing assumptions about who is doing what, how and when communication will occur, expectations for interaction, how one person's work is interdependent with another's, etc.

The importance of operating artefacts was evident in Project A because their absence contributed to negative outcomes for the engineering students:

> The team did not have a Shared Mental Model (SMM) for many aspects of the project. This was a challenge for the engineering students as they did not share important knowledge that they needed to accomplish their work. For instance, they lacked a SMM of task procedures, task strategies, task component relationships, roles and responsibilities, and communication channels, among others … Furthermore, lacking effective communication and a shared mental model, it was difficult to develop trust … The engineering students left the project feeling very dissatisfied with the experience and their interactions with the other disciplines. Much of the conflict stemmed from a lack of effective communication. (Beddoes and Nicewonger 2019a, 5–6).

Had more attention been paid to establishing operating artefacts at the beginning, and following the practices and procedures they laid out, the team would have developed more components of a shared mental model for both the task and team aspects of the project. An example of an operating artefact would be a team workflow chart or team operating agreement that includes a list of each person's responsibilities, communication preferences and expectations, plans for addressing conflicts, and a project timeline with intermediate deadlines. Further information on team operating agreements can be found in Borrego et al. (2013), Ohland et al. (2015) and Davis and Ulseth (2013).

3. Levelling Artefacts: The purpose of levelling artefacts is to prevent *disciplinary capture*, or hierarchy among the disciplines in which one discipline's priorities, goals, methods, or decisions become dominant. They should ensure that each discipline's goals, needs and wants are taken into account and valued in equivalent ways. The concept of *disciplinary capture* comes from research on interdisciplinary collaboration in environmental science (Brister 2016). It 'occurs when the standards, value commitments, and methodological presuppositions of one discipline … consistently take precedence over other disciplines', thereby playing an outsize role in how the ostensibly integrative interdisciplinary research progresses' (Brister 2016, 84). Brister found that 'when a crucial decision is made in a way that draws on standards or concepts from one discipline rather than another, further decisions are likely to settle in place in a way that follows from and supports the initial decision, causing team members from the neglected disciplines to feel increasingly less involved and therefore less invested' (2016, 84).

Disciplinary capture occurred from the architecture side in Project A and circumscribed participation from engineering students in important ways (Beddoes and Nicewonger 2019a). The result was that the engineering students did not have sufficient ownership over the project to result in it being a successful collaboration for them (Beddoes and Nicewonger 2019a). As the mechanical engineering capstone design instructor summed up his impression to the students: 'You had a hierarchy of groups … You were told what your solution was … You felt at the end frustrated, stressed, and your ownership is modest. Appropriate agency matters on how these things work out. You needed to have more agency over all of this' (5). The disciplinary capture also meant that the team lacked positive interdependence necessary for interdisciplinary learning among all team members:

> Interdependence was present, but in an uneven, ineffective manner. That is, the engineering students' work was highly interdependent with the architecture students' work, but the architecture students operated largely independently of the engineering students. Rather than facilitating interdisciplinary learning, the uneven, ineffective interdependence was a source of conflict for the engineering students. (Beddoes and Nicewonger 2019a, 5)

Conversely, levelling artefacts and practices utilised in Project B effectively mitigated disciplinary capture in one of the teams (Beddoes and Borrego 2014). Naming and discussing the concept of disciplinary capture when designing interventions for interdisciplinary teams could help prevent it, thus increasing the likelihood of equality between participating disciplines and consequently interdisciplinary learning among all students. Furthermore, preventing disciplinary capture will reduce conflict because it reduces the likelihood that non-dominant disciplines will feel left out, ignored, or not valued. An example of a levelling artefact could be a shared project map in which each team member explains why their discipline is part of this project, what they bring to the project, what they need to get out of the project, and their expectations for how they will be included. This could be made following a brief lecture on the concept of disciplinary capture. The Toolbox Dialogue Initiative (2020) has also created activities that can minimise disciplinary capture through in-depth discussions about participating disciplines.

4. Proposing Artefacts: The purpose of proposing artefacts is to propose new (i.e. previously undiscussed) ideas, concepts or designs to the team, either at the beginning of the project or at any point throughout the project. It is important that proposing artefacts be shared and discussed with all team members so that everyone understands the current research or design plan, and when changes have occurred. In other words, they promote a shared mental model in terms of what the task is at any given time. This type of artefact was adapted from the category of 'inclusion artifacts' in Lee's (2007) BNA typology. I changed the name to *proposing artefacts* in the interest of clarity due to confusion that the term *inclusion artefacts* had caused when presenting this work previously.

The importance of proposing artefacts was evident in both Projects A and B. In project B, for example, when designing a sensing mechanism for a physical rehabilitation system, students from media science and engineering used scholarly articles, literature reviews, web sites, presentation slides, and drawings on white boards 'to suggest a certain design plan or feature because the kind of sensing mechanism chosen would affect the work of everyone on the team' (Beddoes, Borrego, and Jesiek 2011, 8). However, the importance of proposing artefacts was most strongly demonstrated when they were absent. In Projects A and B, a large source of conflict was when some team members decided to change research or design directions without communicating the new idea or design to the entire team (Beddoes, Borrego, and Jesiek 2011; Beddoes and Borrego 2014; Beddoes and Nicewonger 2019a). For example, in Project A:

> The prototypes that were created by the engineering sub-team were never incorporated into the project's overall design, since they were unable to align their work with the continual changes that were being made to the project by the other sub-teams. Many of these changes came about unexpectedly, which in turn made several of the assignments that the engineering students worked on ultimately not applicable or feasible. (Beddoes and Nicewonger 2019a, 4)

Any idea or decision that has not been previously discussed and agreed upon, needs to be shared with the entire team, otherwise not all team members will have a shared understanding of the current plan. An example of a proposing artefact would be a sketch that introduces a drainage design that is different from the one previously agreed upon and that is then shared and discussed with all team members.

5. Aligning Artefacts: The purpose of aligning artefacts is to align and coordinate shared understanding of a certain aspect of the team's task. Developing such alignment and coordination promotes a shared mental model, promotes trust, and reduces conflict. This type of artefact was adapted from the category of 'compilation artifacts' in Lee's (2007) BNA typology. I changed the name to *aligning artefacts* in the interest of clarity due to confusion that the term *compilation artefacts* had caused when presenting this work previously.

The importance of aligning artefacts was evident in Projects A and B (Beddoes, Borrego, and Jesiek 2011; Beddoes and Nicewonger 2019a). For example, the story below presents an instance in which more effective use of aligning artefacts would have been helpful:

> ... the Computational team encountered challenges related to incongruence in task-related mental models. This became evident during one particular meeting when assumptions were uncovered and questioned about the desired mode of feedback to users of the system they were building. Significant tensions arose because some students thought the media feedback to users would be screen-based, while others had been working under the assumption that they were moving away from screen- based feedback to other types of interactive feedback. These two divergent beliefs about the feedback meant that the team had been working towards different – and incompatible – goals and expectations regarding the development of the system. It is true that meetings like this are part of the *process of developing* SMM; however, at that point, some

> students thought the decision had already been made, which was the source of tension. (Beddoes and Borrego 2014, 245)

In this case, had aligning artefacts been utilised the team would not have reached this point of conflict. An example of an aligning artefact would be further iterations of the new drainage design (proposing artefact above) that the team refines until they are all in agreement on the new design.

6. Structuring Artefacts: The purpose of structuring artefacts is to communicate the overarching, guiding vision for the project, establish ordering principles, and direct and coordinate the activity of the team (Lee 2007). Structuring artefacts help to guide the project at a high level. Similar to aligning artefacts, but operating at a higher level, structuring artefacts can also serve to promote a SMM, promote trust and reduce conflict. Structuring artefacts were first conceptualised in Lee's (2007) BNA typology.

In Project A, a structuring artefact played a prominent role. The team referred it to as the 'project narrative.' It was essentially a script that described the vision and goals of the team's design. It was used to introduce new team members to the project, for promotional purposes, and for communicating the overarching purpose of the design project (Nicewonger and Beddoes 2017).

> The engineering students were introduced to the design project through a project narrative at a joint meeting facilitated by the project's team leaders. This presentation was accompanied by richly illustrated images of the design site, including renderings of both the tiny-home's interior and exterior layouts. In presenting the aims of the project, the team leaders encouraged the engineering students to be innovative, and they asked them to look for ways to further expand on the project's design. The engineering students left the meeting excited to be a part of the project. (Beddoes and Nicewonger 2019a, 4)

Ultimately, however, the project narrative was more useful among the architecture students than it was among the engineering students because 'it was not sufficient on its own to create a SMM. It was created by the architects, and while it was useful to them, their over-reliance on the narrative alone when communicating with other sub-teams contributed to the lack of a SMM' (Beddoes and Nicewonger 2019a, 6). The result for the engineering students was that 'over the course of the semester, their enthusiasm began to waver. By the end of the semester, their project took a radical turn … resulting in high levels of dissatisfaction' (Beddoes and Nicewonger 2019a, 4). Rather than engaging a full range of ITAPs, this team's over-reliance on one structuring artefact ultimately created conflict. Therefore, while structuring artefacts are important, they must be used in conjunction with the other ITAPs presented here. Project narratives can be useful examples of structuring artefacts, but only if they are created with equal input from all participating disciplines. A design concept map would be another example of a structuring artefact (Lee 2007).

5. Conclusion

Student teams cannot simply be thrown together with the assumption that effective learning and teamwork will happen automatically; teamwork skills must be proactively developed (Beddoes and Borrego 2014). Formal mechanisms and spaces are needed to produce shared knowledge (Amey and Brown 2004; DuRussel and Derry 2005; O'Donnell and Derry 2005; Reich and Reich 2006). This is especially true for interdisciplinary teams because of the additional challenges they can encounter. ITAPs provide a conceptual framework and pedagogical tool for promoting desired interdisciplinary teamwork outcomes and minimising undesired outcomes. ITAPs can be proactively utilised by instructors and students to minimise conflict and promote shared mental models, trust and effective interdependence. Naming, discussing and facilitating these teamwork concepts and types of ITAPs as a pre-teamwork intervention can help students identify, navigate, and avoid challenges that hinder successful interdisciplinary teamwork. Specifically, introducing them to the concepts by identifying the different components of a shared mental model and the corresponding ITAPs in Table 2, explaining why they matter, and creating activities and materials to help students establish all four aspects of a shared mental model would be useful. This requires time dedicated at the start of the course, as well was throughout, to creating shared understandings and goals though group processing and creation of ITAPs.

Finally, it is worth noting that this typology is also relevant for all student teams, even those that are comprised of students from only one discipline. While the typology is presented in the context of interdisciplinary teams because the research supporting it was conducted with interdisciplinary teams, most of the types are important for any team. Levelling artefacts would be the one exception. The teamwork concepts explained in the Literature Review and used to conceptualise 'successful' teamwork are not specific to interdisciplinary teams.

Notes

1. In this article, the term 'interdisciplinary' is taken to mean simply a team composed of people from different disciplines, with nothing implied about their level of integration. The typology is relevant to all such teams, with most of the types also being important for even single discipline teams.

2. Artefacts are defined here as objects, either physical or digital/virtual, created and/or used by people.
3. That study systematically reviewed 104 articles (narrowed down from 713) about engineering or computer science team projects published between 2007 and 2012. It covered the databases that include the primary journals in engineering education, science education, management, business, and other relevant fields: Education Research Complete, Academic Search Complete, Psychology and Behavioural Sciences, and Business Source Complete. Several types of methodological validity were utilised. Given the scope of that review, its relevance to engineering education specifically, and its resonance with the ethnographic data informing the article at hand, other teamwork concepts were not specifically sought out.
4. Social loafing is not included in this article because social loafing was not a problem in the studies that informed this typology. Social loafing was not excluded prior to data collection, but rather after analysis revealed that it did not emerge as an issue in these teams. Additionally, social loafing does not pose any particular challenges to interdisciplinary teamwork compared to single-discipline teamwork, and social loafing is not related to interdisciplinary communication in the same way the other concepts are.

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