

Instructors' beliefs and practices regarding mathematical modelling at the periphery of STEM

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This paper reports a study of 10 post-secondary STEM (Science, Technology, Engineering, Mathematics) instructors' beliefs about mathematical modelling and the role of mathematics in STEM coursework. The participants were selected from STEM disciplines that are atypical to the literature base (e.g., anthropology and geography), in order to extend what is known about STEM instructors' beliefs to other disciplines. We conducted episodic narrative interviews to hypothesize the genesis of participants' most salient beliefs. We then conducted a cross-case synthesis to reflect on the similarities between our participants' beliefs and findings previously reported in STEM education literature. Our participants held many beliefs in common with typical STEM instructors with regards to how they define modelling, the role of modelling in STE (Science, Technology, Engineering) courses, and their views of students as learners of mathematics and modelling. Our analysis suggests participants' commitments within these categories are interdependent and arise from lived experiences. Additionally, participants within the same field held competing beliefs about modelling, suggesting that constituting 'major' as an independent variable in future research may not be straightforward.

Keywords: mathematical modelling; teacher beliefs; postsecondary education; narrative analysis

Introduction

Mathematical modelling (hereafter: modelling) is generally thought of as the process of solving real-world problems using mathematics. Engaging in modelling can support students in developing competence towards creative problem solving and experiencing the relevance of mathematics (Blum and Niss, 1991).

However, teaching modelling requires high levels of content knowledge about modelling, including the root mathematical and real-world knowledge, knowledge of different kinds of teaching methods, and knowledge of supports for students (Kaiser,

2017). Therefore, one obstacle to providing students with more experiences with modelling is persuading STEM instructors that doing so is achievable and worthwhile.

Instructors' beliefs are one critical facet of goal-oriented decision-making that influences the decisions instructors make in the classroom (Schoenfeld, 2011). The connection between instructors' judgements about their pedagogical practices and their beliefs has been documented by many researchers across educational contexts: K-12 science (Haney et al., 2002), K-12 mathematics (Bray, 2011; Clark et al., 2014; Jacobson, 2017; Yurekli et al., 2020), college sciences (Gibbons et al., 2018; Pelch & McConnell, 2016), and engineering (Borrego et al., 2013b).

Research has documented instructors' beliefs about modelling, integrating mathematics with science, and the characteristics of successful STEM students. Researchers typically have taken STEM to mean physical sciences, engineering, and computer science, and accordingly, recruited instructors from these disciplines. However, many disciplines, such as psychology, geography, and anthropology, are relying more and more on mathematics and statistics to further their research and industrial practices. For example, psychologists measure stress levels using skin sensors to describe or predict participants' responses to a particular stimuli (Broudy, 2019). Given this trend, we infer that modelling is becoming more prevalent in these disciplines, and teaching of modelling is becoming increasingly indispensable in disciplines that previously did not rely heavily on mathematics. Yet, we know comparatively little about how professionals in disciplines whose roots are not mathematical (or statistical) conceptualize modelling or their views on the role of modelling in their coursework.

Articulating an empirically informed account of what constitutes modelling in disciplines on the periphery of STEM disciplines can provide novel perspectives about

modelling instruction absent from the literature. Such perspectives can better inform the teaching and learning of modelling by expanding the contexts in which modelling is studied (or to which mathematics is applied), and potentially incorporate disciplines and student demographics not currently accounted for in literature in future research, such as female-dominated psychology and biology (see National Science Board, 2019).

This study lays the groundwork for expanding the field's view of STEM instructors' beliefs about modelling. The goal of this paper is to extend what is known about STEM instructors' beliefs about modelling in STEM majors' course work by documenting perspectives from disciplines unaccounted for in the literature base.

Literature Review

STEM Instructors' Views on Modelling

Historically, researchers have viewed STEM instructors' beliefs about mathematics' relationship to their disciplines as informative about their views on modelling and its place in their courses because instructors' views of this relationship are likely tied to its application in their disciplines. For this reason, many studies examine industry professionals' views of modelling. Participants who worked in industry or instructors of engineering or mathematics who taught modelling have voiced that: 1) models are used to describe the relationships among variables abstracted from real-world phenomena 2) models are useful for understanding specific phenomena in the real world 3) modeling modelling is similar to problem solving but requires setting up and validating equations through compromise among variables, structure, and risks (Drakes, 2012; Frejd & Bergsten, 2018; Gainsburg, 2013). Participants in these studies further described models as useful for understanding specific phenomena in the real world. They described the process of modelling as similar to problem solving but additionally, modelling requires

setting up and validating equations through compromise among variables, structure, and risks. Interestingly, Gainsburg (2013) reported that none of the professional modelers mentioned computer modelling, which was taken to mean either a theoretical model that underlies some software, or a specific representation of a computer generated object. Computer modelling was also absent in the studies conducted by Frejd and Bergsten (2018) and Drakes (2012).

Holmberg and Bernhard (2017) exposed contrasting views held by 22 university instructors teaching Laplace transforms with regards to their disciplines' relationship to mathematics. The STEM instructors expressed a spectrum of views ranging between two extremes, that mathematics, physics, and technology are inseparable to the opposite view, that these disciplines are not related at all. The theme of separated versus integrated mathematics was touched on by Nathan et al. (2010) who studied two samples of engineering instructors' beliefs about students' success. One sample had experience using an integrated STEM curriculum while the other sample had experience teaching mathematics or mathematics and science. The latter sample were least likely to claim their class was integrated with STEM and more likely to agree that high levels of achievement were requisite for successful STEM careers. This theme resurfaced in Bergsten et al.'s (2015) interviews with two professional engineers about their views of conceptual and procedural mathematics skills in engineering education and practice. One engineer, Robert, from Sweden, worked in technical physics and electrical engineering. The other engineer, Ben, was a civil engineer from South Africa. Both held that conceptual mathematics skills are the most important for engineering education. However, Robert emphasized the connection between concepts and procedures, implying a strong integration between engineering and mathematical knowledge. In contrast, Ben stated that procedural mathematical skills are unnecessary, implying at

least some degree of separation between the two domains of knowledge. Bergsten et al. (2015) conjectured that this distinction was due to the engineers' differing disciplines and backgrounds. Overall, these studies showcase two ideas about modelling and curriculum present in Kaiser (2017) different disciplines view applied mathematics, which includes modelling, and pure mathematics as either separate (and, consequently, should be taught separately) or as inseparable from the subject therefore inherently part of other sciences (and, consequently, should not be taught separately).

An adjacent body of literature focuses on STEM instructors' beliefs about characteristics of successful STEM students, particularly their beliefs about students as learners of science, mathematics, and modelling. Remillard (2005) suggested that instructors' views of their students are tied to their views about the role of modelling in their course work. Faulkner and Herman (2016) found that engineering and computer science instructors valued algebraic fluency, quick computations, symbol sense, ability to use online tools to solve mathematics problems, confidence, and other modelling skills. Similarly, Gandhi-Lee et al. (2015) interviewed biology, chemistry, computer science, engineering, geoscience, health science, mathematics, and physics instructors. Their participants held that to be successful, students must be curious, independent problem solvers, with positive attitudes. Additionally, Gandhi-Lee et al. (2015) found that these instructors identified mathematics overall as a roadblock to success, and specifically identified algebra as the minimum requirement for success. Taken together, these studies suggest that instructors' views of their students as learners of mathematics are tied to beliefs about curriculum.

Summary

Overall, researchers have documented how professional engineers' and instructors of engineering and mathematics conceptualize modelling. Instructors in these disciplines,

as well as secondary and post-secondary science teachers, have shown evidence of a plurality of views when describing the role of mathematics in their classes (Nathen et al., 2010; Bergsten et al., 2015; Holmberg and Bernhard, 2017). STEM instructors more broadly, including computer science, health and geo sciences, biology, and chemistry, have well-considered characterizations of student qualities they believed contributed to success (Gandhi-Lee et al., 2015; Faulkner and Herman, 2016). Educational researchers have yet to learn how disciplines at the periphery of STEM conceptualize modelling and how those instructors' view on modelling plays a role in educating their students. Expanding the focus of mathematics education research to attend to beliefs and perceptions of instructors in peripheral STEM disciplines will expand the applicability and generalizability of results and theories already found in the existing literature. With this goal in mind, the purpose of this study was to address the question:

How do beliefs and practices about modelling of instructors in peripheral STEM fields comport with existing research on central STEM instructors' beliefs and practices?

Studying STEM Instructor Beliefs and Experiences

Researchers take many approaches to studying the relationship between instructors' beliefs and their pedagogical practices. In this next section, we synthesize literature on how instructors' beliefs are studied, and conclude with our perspective on studying beliefs.

Different methods to study beliefs.

Studies that used strictly quantitative methods for studying instructor beliefs used some form of regression for the purpose of predicting instructor beliefs based on other constructs. Data were typically collected via validated beliefs assessments while

also gathering data on predictor variables such instructor content knowledge, and experience (e.g., Clark et al., 2014; Jacobson, 2017; Yurekli et al., 2020). Examples using instruments to measure instructors' beliefs span all academic levels including primary, tertiary, and also span content areas, including mathematics, science, and engineering (e.g., Clark et al., 2014; Gibbons et al., 2018; Jacobson, 2017; Pelch & McConnell, 2016). Philipp (2007) conducted a systematic literature review about instructor affect and beliefs, noting a tendency to use an instrument to measure instructors' beliefs in conjunction with data about teaching practices in statistical models to discuss the significance of the relationship between instructor beliefs and instructional practices. This tendency has been noted and critiqued in broader higher education literature. For example, Devlin (2006) challenged the notion that there is a clear causal relationship among instructor conceptions, practices, and student learning. This notion could be why many of the empirical studies about instructor beliefs employ a mix of qualitative and quantitative methods.

Of course, some studies do employ purely qualitative methods to assess beliefs. For example, Wang et al. (2020) presented a case study of six instructors from two high schools attempting to collaborate with the aim of integrating STEM into their instructional practices. The goal of this study was to describe the instructors' beliefs about instructional practices around STEM integration. These six instructors were split into teams of three. The case study was used to understand the instructors' beliefs and instructional practices when trying to include a STEM integrated task, in this case a hydroponics task, into their classrooms. They found that the success of this endeavour hinged upon the team sizes (instructional practice), teaching goal (instructor belief), and collaboration among instructors (instructor belief). Though Wang et al. (2020) did use qualitative methods, the teachers' beliefs were still conceptualized as a static construct.

Other lines of inquiry about teacher beliefs include a dimension for change in beliefs, with attention to how and under what conditions - teachers' beliefs change. For example, Lebak (2015) described the relationship between beliefs and practices and how beliefs changed through a case study of a 5th grade science teacher. This study found that beliefs and practices can be characterized as a feedback loop. Beliefs influence pedagogical practices which in turn can change or reinforce the teacher's beliefs. Another example would be Pelch and McConnell (2016), whose goal was to determine the efficacy of a professional development program for geoscience instructors to change their views toward more student-centred practices. They used the Teacher Belief Interview (qualitative) and the Beliefs about Reformed Science Teaching and Learning survey (quantitative) to assess their beliefs about student centred practices before and after the professional development program. They found that the professional development program did in fact change the scores on these assessments towards a more positive view of student-centred instruction.

Some research has been done on how a teacher's background might influence their beliefs. For example, Clark et al. (2014) used professional background and teaching experience in their model for predicting teacher beliefs. As well, Jacobson (2017), included demographic information on their mathematical model to predict teacher beliefs. These studies used quantitative methods to identify what types of experiences (professional background and teaching experience) and personal characteristics (demographic information) most influence a teacher's beliefs about teaching and learning. However, one limitation is they lack explanation as to how and to what extent those experiences may influence a teacher's beliefs; another is they do not offer explanation as to how the teachers came to hold their beliefs about teaching and learning. In contrast, (Kaasila, 2007b) discussed the genesis of pre-service teachers'

identities as mathematics teachers, suggesting it may be fruitful to seek an explanation for how a teacher comes to hold certain beliefs about teaching and learning.

Overall, research on teacher beliefs uses a combination of qualitative and quantitative techniques (e.g., Borrego et al., 2013a; Bray, 2011; Gibbons et al., 2018; Haney et al., 2002; Pelch & McConnell, 2016). A typical approach uses quantitative methods to build statistical models to assess teacher beliefs' influence on instructional techniques. For example, quantitative studies have pointed to ways that STEM instructor beliefs are associated with teacher content knowledge and experience (e.g., Clark et al., 2014; Jacobson, 2017; Yurekli et al., 2020); and that professional background, experience, and demographics can predict teacher beliefs (Clark, et al., 2014; Jacobson, 2017). In doing so, this literature treats teacher beliefs as a static construct. Even those studies that do not treat beliefs statically, do so by discussing how one construct (such as teacher practices) or professional development program influences or changes teacher beliefs (Lebak, 2015; Pelch & McConnell, 2016). However, these studies leave open questions about how teachers came to hold their beliefs. The literature reviewed here suggests that (1) uncovering the genesis of STEM instructors' beliefs would reveal important information about their instructional philosophies regarding the inclusion of modelling in their curricula and (2) that qualitative methods are preferred when studying *individuals'* beliefs. Yet, research also suggests that overly broad characterizations can arise from thematic analysis of large data corpuses. Overly broad characterizations occur because thematic analysis does not allow a fine enough grain size to develop local causal models connecting individuals' instructional choices to their circumstances. We describe our methodological and procedural choices for achieving this balance in the next section.

Theoretical Orientation and Methodology

Narrative research, as a method of research, involves describing experiences expressed through the stories told by individuals (Creswell, 2007). We adopt the following stances compatible with narrative research. Beliefs are knowledge a person holds that is either descriptive, evaluative, prescriptive, or any combination of the three (Pajares, 1993). A person's identity, personality, desires, and importantly, their beliefs are embedded within the stories they tell (Loong, 2019). A story is a narrative preserving of 'the complexity of human action with its interrelationship of temporal sequence, human motivation, chance happenings, and changing interpersonal and environmental contexts.' (Polkinghorn, 1995, p. 4). Thus, a story is more than a chronological ordering of what happened, it has also an underlying structure connecting the events through choices made by the storyteller. The structure, or plot, aids in identifying how participants connect the events in their lives as precursors for and consequences of the choices they make. This orientation affords a view of STEM instructors' stories as embeddings of their beliefs about the role of modelling in the education of STEM majors, as described below:

A STEM instructor holds beliefs about modelling (even if they do not use the label 'modelling'), in contexts including their research, industry jobs (if applicable), and teaching. An instructor can have an experience, a notable instance salient to them, that may affect their beliefs about modelling.

Consequently, analysing the stories STEM instructors tell about their experiences with modelling in their personal and professional lives will afford inferences regarding the nature of those beliefs. Descriptive-analytic accounts of the instructors' stories also articulate explanatory mechanisms for how individuals came to hold their beliefs, information useful for future research.

The National Science Foundation (NSF) published a list of 31 disciplines in STEM (NCSES, 2014). We took ‘STEM instructors’ to mean individuals who are professionals in those disciplines and teaching in those academic units at university. Thus, participants were likely to have experience with modelling in their research work or industry jobs, and therefore have stories to tell about the role of modelling in the education of majors in their discipline. We recruited participants from a large university in the southwestern USA who practice in disciplines that are not typically found in the modelling or education literature (i.e., not mathematicians, engineers, or physicists). We identified 54 peripheral STEM instructors who taught the semester before data collection, of whom 10 (two economists, two anthropologists, three geographers, and three psychologists) volunteered to participate.

Data Collection

We conducted episodic narrative interviews (Mueller, 2019) over Zoom. The episodic narrative interview is a fusion of three qualitative techniques: semi-structured interviews, narrative interviews, and episodic interviews. This approach provided a strategy for looking at experience-centred narratives which allowed for the participants’ views of salience to be prioritized, allowed for exploration of instructors’ beliefs about modelling (the target phenomenon), and enabled cross-participant comparisons (Mueller, 2019) as well as comparisons to the extant literature.

Episodic narrative interviews are organized to funnel the interviewee’s story towards the phenomenon of interest (Mueller, 2019), illustrated in Figure 1. First, the interviewer asks a question defining the phenomenon of interest. She then elicits an episode from the participant’s everyday life in which the phenomenon of interest would take place. Next, she follows up with questions about the phenomenon of interest within that evoked situation. Questions like *how does modelling fit into your class as a whole?*

and *how does modelling fit into your students' major (course)work?* elicited responses that intimated the instructors' beliefs about the role of modelling in the education of STEM majors. We organized the remaining protocol around two sub-stories, building one cohesive story to state and explain the instructors' beliefs about modelling in their classrooms. The first sub-story focused on experiences with modelling outside of teaching. The second sub-story focused on the instructors' experiences with modelling while teaching. The mathematics education field has come to consensus that there are different perspectives about the purpose of including mathematical modelling in mathematics classrooms (Kaiser, 2017) and that each corresponds to a differing operationalization for the term. For our participants, we were careful to not define modelling in the interview. We made this decision because our purpose was to uncover what our participants viewed as modelling, not to evaluate their knowledge of what mathematics educators view as modelling.

Data Analysis

In accordance with our theoretical lens, embedded within the STEM instructors' stories are their beliefs about the role of modelling in the education of STEM majors.

Consistent with this assumption, we used analytic techniques informed by narrative inquiry, identifying key plot points (core beliefs), creation and refinement of plots, creation and refinement of narratives that follow the plots, which we elaborate as follows. All 10 interviews were analysed at the latent level (Braun & Clarke, 2006) via the method of constant comparison (Creswell, 2007). The grain size for analysis was finished thoughts, operationalized as statements about the same topic where a change in topic indicated a new thought. Latent analysis was conducted in five phases: becoming familiar with the data, generating initial codes, looking for themes within the initial codes, reviewing those themes for refinement, and defining the themes. When new

themes emerged while coding, we went back to already coded interviews to integrate and refine the new theme. This analysis led to a set of codes providing overarching ideas about the instructor's beliefs and practices regarding modelling. We then used the Max Maps feature in the qualitative data software MaxQDA¹ to identify each participant's core beliefs. We operationalized a core belief to be a commitment a participant voiced at least twice during the interview (see Figure 2).

To account for important background information, significant experiences with modelling in daily life, and significant experiences with modelling while teaching, we conducted *emplotment analysis* (Polkinghorn, 1995) to probe and then reconstruct the data. The first step was to identify each participant's set of core beliefs. The next step was to hypothesize a plot which was then tested against the data via asking questions like: *do any major events conflict with this current plot structure?* If a major event from the data conflicted, then changes were made to the plot, and the revised plot was tested against the data again. Additionally, we addressed pertinence. If an event was not pertinent to the plot, that data was culled from the story in a process called narrative smoothing (Kaasila, 2007a; Polkinghorn, 1995). This process was undertaken until a cogent plot emerged that considered only pertinent events. The result was a plot outline which was then filled in with data elements to form the final coherent story (Kaasila, 2007a; Polkinghorn, 1995).

¹ MaxQDA is a proprietary qualitative data analysis software that enables researchers to systematically seek and articulate patterns in records like audio/visual recordings and transcripts. The software supports qualitative coding techniques and a variety of visualization tools for generating hypotheses about the relationships among qualitative categories.

A sample plot outline for Haven is in Figure 3. Emplotment analysis produced individualized narratives tying each participant's core beliefs with important background and significant experiences with modelling both in daily life and while teaching (see Figure 4 for an example from Haven's analysis).

Table 1 reports participant pseudonyms, their disciplines, and participants' most salient beliefs about modelling at the time of the interview. After constructing individual narratives, we analysed the narratives collectively, using techniques from thematic analysis (Braun & Clarke, 2006), to look for overlap between the themes we identified and those present in the literature.

Results

Collectively, we inferred twenty-five distinct core beliefs across participants, displayed in Table 1. Each participant exhibited between three and nine core beliefs. Table 2 summarizes the four most-commonly held core beliefs among all participants (beliefs referred to multiple times by at least half of participants). We note that the methodology required us to attend to the aspects of participants' lives most salient to them as they shared stories from differing phases of their lives. Thus, not all participants expressed all beliefs. Indeed, there was no core belief expressed by all participants and some participants expressed opposing positions on salient topics. No participant held a completely non-overlapping set of core beliefs. In the following sections, we present emplotted narratives for six of the ten faculty. These six narratives were chosen to showcase the narrative this analysis yields, while also highlighting a broad range of core beliefs and connections to previous literature. We use them to inform the cross-case analysis in the discussion.

Karter's Story

Karter (economist) researched international and regional economic systems and fiscal policy. He regularly taught first-year undergraduate courses and courses in his department's masters' program. He had taught other macroeconomics major courses at a previous institution. His academic background is suggestive of an accomplished and ambitious student. He earned his undergraduate degree at one of the top universities in eastern Africa², majoring in economics with the academic equivalent of a minor in mathematics. He graduated at the top of his class and received a scholarship for a master's program in economics at a university in the USA. After graduation, he applied to various doctoral programs. While seeking the right program, he worked as an economist and as a time series modeler for a major international bank. After completing his PhD, he took an assistant professor position at a university in California before moving to his current position, as an associate professor of economics.

Karter discussed the different modelling projects he participated in, ranging from international investment strategies to developing economies. Recently, he began research on the impacts of the COVID pandemic on minority populations within the US.

Karter emphasized the idea of modelling as a statistical process, but he also discussed how each statistical process comes with its own set of values and assumptions. He explained that within the field, there are different philosophical views of economics which affect the kinds of models economists use and assumptions that go into the models. The examples of models and modelling he gave, both in research and in the classroom, involved fitting curves to data using statistical methods.

2 We have blinded the specific country to protect participant confidentiality.

Karter felt strongly that modelling is important for students to understand and be able to do. His commitment towards teaching modelling in his classroom was rooted in his conceptions of the relationship between economics and mathematics. He described the two domains as ‘too integrated together’ to talk about as two separate entities. He preferred to focus on mathematics to incentivize his students to learn it. To encourage his students, he tells them, ‘You can ask all the questions you want and I will be here for you.’

His beliefs about the centrality of modelling to his field are also tied to his experiences modelling for big companies, which can powerfully influence large and small economies. He felt that every student should *have the right* to know how the economy functions and behaves. Because of his commitment to ideals about modelling as a means to achieve a right, we would associate Karter’s view of modelling with the sociocritical perspective of modelling, which ‘emphasizes critical thinking about the role of mathematics in society’ (Kaiser, 2017, p. 274). His sociocritical perspective was apparent in his instructional design decisions. Since he felt that explicitly teaching modelling to his students was important, he sought to motivate his students to deeply learn the mathematics that showed up in his courses. To motivate his students, he would share stories of his childhood, like the following one he told during the interview.

Karter came from an impoverished nation and was born to a not-so-well-to-do family. While he was growing up, the government gave university scholarships to only to the secondary students who scored in ‘the top 1%’ on a national standardized exam. There were about 50 mathematics questions on the exam including calculus, differential equations, statistics, and other topics. He was a mathematics major in secondary school and wanted to attend university. Thus, the pressing need to obtain a scholarship motivated him to stay up every night studying for the exam. He and a group of friends,

who were also sitting the exam, would study by solving ‘all the math problems for the last 30 years’ from past exams. Sometimes, they would study by candlelight because the electricity would be out. On the weekends, the friends would go to their teachers’ homes to ask questions. The Friday before the exam, they visited a teacher to ask about a trigonometry problem they were having trouble answering. Neither his teacher nor his study group found the answer to that question. Though discouraged, Karter did not give up. He stayed up until he solved that problem. He recalled ‘at 05:00 in the morning, I figured out how to prove that long trigonometrical proof. . . I actually found there were shortcuts, there were two other shortcuts where you could actually do and get to the same proof. And that was the best moment ever. I was screaming and jumping.’ Despite being exhausted, he went to the exam (at 9:00 am) and was happy to see that the exact question was on the exam. Afterwards, Karter’s friends went to him and lamented that they had given up. He recalled ‘it [was] only me who get that scholarship for that university. That taught me a lesson, the importance of math in what I do.’

Karter, through his story, learned: mathematics is very important, and anyone can learn it with motivation and persistence. Thus, Karter saw mathematics as empowering in two ways — one way was that learning mathematics keeps open doors that are shut to people who do not learn it and the other way was that learning mathematics enables ordinary people to understand how the large societal systems around them work. This ideology transfers to his views on modelling, as Karter tended not to distinguish between applying mathematics and doing modelling in his work.

Phoenix’s Story

Phoenix (anthropologist), who had been with the same department for decades, normally taught two courses, an introductory course and one on film. He also taught a series of three rotating seminars, including one integrating economics with

anthropology. His research priorities included questions of ethnic identity, religion, and commerce. At the time of the interview, he was studying the institutional origins of anthropology in the United States between 1880 and World War I. Phoenix described his research as ‘humanistic’ and ‘heavily cultural.’ He shared that the last time he had conducted any sort of quantitative work was during his dissertation, which required simple *t*-tests to detect a significant difference between two populations. Due to his research experiences, he believed that modelling was not important to his field.

He stated the same was also true for the courses that he teaches. That is, neither mathematics nor overt instruction in modelling were common in the undergraduate anthropology classes. He did describe the closest he came to teaching modelling in his courses was showing grade distributions to his students. He recounted that when COVID forced his ‘face to face, old fashioned lecture’ instruction to an online modality, he promised his students that the grades for the course would not differ from the grades from in-person instruction. Phoenix realized that keeping that promise entailed having ‘a model of what the class should look like in terms of the distribution of point grades and letter grades.’ He used this information to provide a wide variety of options that would ‘enable students to recover from poor [test] grades’ to ‘reproduce that normal curve.’ His model-based policies convinced his students that they were learning the material and that they were engaging in the same quality of instruction as they typically would have before COVID.

Phoenix talked about one elective undergraduate course called Economic Anthropology that sometimes occasioned the opportunity for him to touch on more mathematical concepts. His intention was to teach overarching abstract theories, rather than nitty-gritty economic analysis and so he chose to gloss over some of the details of

the computations and theorems. About his choices, Phoenix was relieved, since it was ‘not my job and truthfully, I am not qualified to do it.’

Phoenix conceived of modelling in terms of statistical processes. For him salient examples of models were the distribution of students’ grades and his own dissertation employing *t*-tests to obtain results. He held the belief that a model is an equation that ‘replicates’ a real-world scenario. The equation could be derived using either a statistical process or some other type of method he was not familiar with but knows vaguely about because his son was a computational mathematics major. Because of this close experience seeing his son’s use of models, Phoenix said he knew a bit more about modelling than he did even a couple of years prior. Despite his appreciation for the modelling his son did, Phoenix justified his commitment not to focus on mathematical concepts and their applications in his classroom in terms of their lack of applicability in the research he conducts.

Riley’s Story

Riley (anthropologist) normally taught several upper-level undergraduate and graduate level classes in archaeology. At the time of the interview, he had two PhD students working with him. His research priorities included ice-age hunter gatherers in North America from 14,000 to about 10,000 years ago.

Riley conceived of modelling as a statistical process used for making predictions. For him, salient examples of modelling included carbon dating artifacts to finding the range of dates in which ice age tools are placed in a collection in order to make inferences about events from thousands of years ago. While discussing modelling, Riley brought up the idea of the limitations in modelling. He pointed out that modelling pre-history is essentially making predictions about what might have happened, not a statement of definite truth. ‘I often think mathematical modelling is misunderstood as

being some claim to reality, but the truth is like in pre-history that's not necessarily something that can actually happen.'

During our discussion of the definition of modelling, Riley noted he was hesitant to participate in the interviews. He said, 'I feel a little self-conscious because I'm not much of a mathematical person and I suspect you are and so probably it wouldn't surprise me if I'm misusing concepts and terms. I'm only an anthropologist.' His beliefs about his own mathematical ability, compared to colleagues, was salient in how he discussed his research projects. He stated he viewed his coauthors as being better mathematicians and so confers with them when in need of 'complicated mathematics.'

Riley's feelings towards mathematics seem to stem from his experiences during high school and university. Riley explained that he never saw himself as 'naturally good' at mathematics, and that it took a long time for him to develop the mathematical skill sets he needed for classes. He expressed frustration that he often would make small arithmetic mistakes that resulted in him getting entire questions wrong, even though he felt he understood the underlying concepts. These experiences made him insecure in his mathematical ability. However, he gained more confidence when taking statistics in graduate school. Riley described his statistics professor as excellent because they were patient with him, taking time to convey concepts. This experience helped him feel he finally understood statistics for the first time. Though Riley's confidence increased, he remained critical of his own abilities indicating that the faculty in charge of instruction are not mathematically inclined and may explain his hesitancy to deeply discuss modelling tasks.

Riley's feelings towards mathematics also seemed to influence his perceptions of his students as doers of mathematics:

I think if anything, this is often true of Anthropologists, that they're, as an undergraduate student, they weren't people who were terribly comfortable with Math. And it wasn't until I ... Algebra, Trigonometry, never sat well with me. But, when I started taking stats classes, that made more intuitive sense to me, and I think it's statistics, and my experience with statistics, that gave me confidence to then incorporate other mathematics into research without being quite as daunted, quite as intimidated.

Riley's characterization of students as not mathematically inclined, in turn, influences the way he talks about mathematical applications in his classes. He says he is very focused when introducing mathematical applications to his classroom, keeping the instructional plan relatively simple. One of Riley's goals is introducing anthropology majors to concepts like carbon dating, without making them afraid to move forward. Riley speculated that his undergraduate students get their experience with mathematics in actual mathematics classrooms. He noted that his job is to teach them core concepts of his field, which sometimes involves discussing some mathematical applications. However, he noted that teaching the mathematics is not his priority. These commitments feed into his view that modelling instruction is best suited for graduate students in the discipline.

However, Riley also indicated that it is very important that during mathematical instruction, students are given the opportunity to connect those mathematical concepts with real-world applications. He reported that his students would get a little bit more interested in certain topics whenever applying the mathematics they learned. Underlying his statements is this notion that students would be more inclined to engage in mathematics autonomously if mathematics was connected with the topics they found interesting. Overall, we infer that he believes modelling is a worthwhile practice for

undergraduate students to engage in, but he personally does not feel comfortable facilitating that practice.

Quinn's Story

Quinn (psychologist) characterised himself as a psychophysiolgist, meaning that he measures human psychological processes and relates them to human behaviours and cognition. His research concerned sensation and perception, including attention and consciousness, and other human factors as they relate to engineering psychology and cognitive neuroscience. Quinn taught mainly upper-division undergraduate classes (taken by third- and fourth-year students) such as the psychology of consciousness, and human factors, along with one graduate level course in psychophysiology.

Quinn's road towards his doctorate was winding. As a college student, he felt 'directionless.' He attended college for three years before dropping out to work. He returned to university in his mid-20s, with a strong interest in mathematics and philosophy. Aside from those courses, he also took coursework in physics as electives. At his university, there was a center dedicated to researching consciousness. The concentration immediately piqued his interest because studying consciousness would mean a blend of many disciplines such as psychology, neuroscience, philosophy, mathematics, humanities, and religious studies. To research consciousness, he would need to study both psychology and neuroscience. But at that time, he had nearly completed his undergraduate degree in mathematics, and 'it would have been foolish to just stop' so he decided to continue pursuing both degrees. He earned two bachelor's degrees (mathematics and psychology) with two minors (philosophy and physics). He then joined a graduate program, earning a master's in psychology. Since he also had a strong interest in physics, he also obtained a master's in physics before entering and

completing a doctoral program in psychology. Though the process was ‘a lot of effort and sacrifice,’ he attributed success in his current research to his experiences ‘because it opened up many, many doors for me and I wouldn’t be where I am now if I hadn’t done that.’ For Quinn, modelling was very important to his field because his entire research career was rooted in modelling cognitive processes. He viewed the purpose of modelling as describing and predicting real-world processes of some kind. Quinn acknowledged that ‘there are some subdisciplines of psychology that don’t really do mathematical modelling at all’ but that for any subdisciplines involving studies of the neural or perceptual processes, models are a primary part of the work.

More than other participants, Quinn readily and affirmatively distinguished certain subdisciplines of psychology based on the extent the field is based on modelling. Of our participants, Quinn seemed most attuned to the idea that a given field is not homogenous with regards to mathematical content. His recognition of the heterogeneity in psychologists’ needs for training is reflected in his teaching philosophy. He suggested that modelling, as a topic, might be best suited for students who intended to pursue advanced degrees in those specific subdisciplines (e.g., human factors) though all psychology majors would need to learn some statistics.

Despite his ideals, Quinn experienced barriers to his ability to implement modelling tasks in his classroom. He mentioned an undergraduate course on human factors. He recalled that he wanted students have ‘hands-on experience’ and had them do ‘little experiments in the class, just collecting very simple forms of data and then doing very simple mathematical analysis on that data in order to illustrate some concept, or even just what this field is about, like what a practitioner would do.’ For example, in one experiment a student played the role of the research subject, and they need to detect

when a phone is ringing. The groupmates played the role of experimenters who increased the volumes on their phones from silent. The experimenters then calculated averages to determine the length of time it took for a person to detect when a cell phone was ringing. Quinn found implementing the experiment assignments had ‘mixed results.’ Students struggled with the complexity of some of the questions. He had to simplify the activity to not take up too much class time. However, over the years, he also developed a good eye for when a student might be interested in pursuing a graduate degree and gives them more advanced portions of the activity.

Quinn viewed modelling as central to his courses, even if he had to simplify the scenarios and scaffolding questions for his students. His use of modelling in the classroom falls squarely under ‘science-related goals: imparting a realistic image...giving insight into the overlap of mathematical and extramathematical content’ (Kaiser, 2017, p. 272). His classroom commitments seemed to originate from two sources. First, Quinn was quite comfortable speaking about many aspects of modelling arising from his strong background in applied mathematics across multiple disciplines. Second, due to his research program, he found modelling to be very important for students intending to enter any applied field of psychology and sought to increase their exposure to modelling through content integration (where more than one field is covered at the same time) (Kertil & Gurel, 2016).

Haven’s Story

Haven's (psychologist) research focused on social cognition and how individuals think and reason about social situations. When teaching undergraduate courses, she was usually assigned to the large lecture halls with over 100 students such as lifespan development. As an undergraduate, she earned an applied statistics minor even though she never ‘really had any super quantitative-heavy classes.’ In graduate school, she took

some statistics courses though those did not use the term ‘mathematical modelling’ to describe their content.

In her work, she frequently used statistical methods. For example, she shared a paper she co-authored that featured a complex data set. Participants were involved in ‘multiple conditions’ and they were interested in ‘effects that were nested within participants’. She observed there were many ways to handle that data structure, but she wished to use a more sophisticated approach. At the time, Haven did not know the necessary technique from her previous research or prior training. She discussed the idea with her colleagues, searched online, and learned how to code the procedure in *R*. She described her modelling process as ‘just a ton of Googling and reading stats blogs, and looking at people's code, and figuring out what I wanted to do, and then just trial and error and *R*, until I felt like I had run a model that made sense.’ She was able to produce an adequate model, use it to analyse the data, write her research paper, and publish it. Haven’s story of self-guided learning is an example of modelling using statistical methods being used in her field and is also an example of another core belief: learning happens through experience. She cautioned that she did not believe that learning modelling needed to happen experientially, but that it was the way she had learned modelling throughout her education and academic career.

Her reflection on her learning tied to her teaching philosophy. Haven recounted some of her experiences mentoring graduate research assistants. She broadly characterised many of them as not having the ‘certain mathematical background’ to talk about the ideas and concepts necessary to design, execute, interpret, and communicate studies. The assistants in her lab, for example, often matriculated without the ability to distinguish between independent and dependent variables. She recounted the time she would spend tutoring and mentoring her graduate students in those aspects of

mathematical formalisms. She would purposefully have the student construct graphs that met certain criteria so that the student would learn which aspects of the graphs corresponded to the data analysis. In this way, Haven sought to provide learning experiences for her graduate students that paralleled her own.

Because Haven taught many of the university's large lecture classes, she was responsible for many students and saw great variation among them in terms of levels of mathematical preparedness. Many, especially those in the first-year introductory courses, were not at a competence level to discuss statistical models. She also shared her impression that many were not mathematically inclined, meaning that they did not show much interest in the mathematical explanations for the content she taught. Her inferences attended to the fact that 'over half of them will raise their hands' to being 'bad at math.' Because her students would not appreciate mathematics, she explained that she chose not to dwell on computations nor on mathematical derivations of the origins of the models she needed her students to use. Mostly, she said, she focused on the broad, overarching concepts. She gave an example of such a concept: distinguishing between correlation and causation.

Haven lamented that even in her graduate courses, students would not see many sophisticated mathematical models and almost none in her undergraduate classes. However, Haven disclosed that she felt constrained by the requisites of the psychology major, 'because there's no stats prereq for my course, there's no math prereq. Even trying to explain to students how to interpret the magnitude of a correlation value, that magnitude means it doesn't matter. You can ignore the positive or negative side. That is a challenge, so I don't want to do modelling there.' She mentioned also that when she would try to explain mathematical concepts, the students would become fearful. Due to these negative experiences, she chose not to focus on mathematics. To meet her

instructional goals and obligations she felt to the field, she often worked one-on-one with students who enrolled in independent study courses with her. In the independent studies, she would often encourage students to ‘Google a lot’ of the mathematics they needed to resolve the problems that arose.

For Haven, mathematical preparedness was a key threshold for developing, applying, and analysing models. She often spoke of fluency with graphical representations as being particularly important to the content in her courses and research program. Her experiences led her to view her students—both undergraduate and graduate—as not sufficiently mathematically prepared, and at least beyond the first-year introductory courses, she enacted what (Kaiser, 2017) referred to as subject-related goals: structuring the learning environment around mathematical concepts, methods, and illustrations. This practice explains two core beliefs. Because students are not mathematically prepared, Haven feels she cannot implement modelling tasks. This leads to modelling instruction being uncommon in undergraduate classes. In turn, this leads to identifying specific students to give additional instruction based on their future career endeavours.

Lyric’s Story

Lyric’s (geologist) research focused on natural disasters and economic geography. Lyric is well established in her department, teaching many different courses ranging from natural hazards and disasters to statistical and qualitative methods to history of geography and environmental management.

Lyric obtained her undergraduate degree in a business college and then obtained a master’s degree in economics. Lyric mentioned that she took many different statistics courses. Her background in statistics led to receiving a doctoral research assistantship

working on hazards and disasters, a change from her original intention to pursue a doctoral degree in economic geography.

She gave many examples teaching modelling with the purpose of using those models to predict some phenomenon. Her instruction focuses on the connection between qualitative and quantitative aspects of a model, where the qualitative side is the structure in the real world that grounds the quantitative equation. Her decision to focus on the connection between qualitative and quantitative comes from her experience reading journal articles that she feels use big statistical models just for the sake of having big statistical models and not for clarity or more predictive power.

The most important being, I would like, in addition to the modelling, especially when you're writing up for publication, I would like to see less emphasis on the model itself and what it predicted, and more emphasis on the application. ... Not enough is worked in. Some of these scientific journal articles you can't even read. And I'm wondering, this is just a waste of NSF's money, because there's a lot of math in them. It's like a priesthood of the math, and it doesn't accomplish ... it predicts for one location, maybe, and it looks great and sophisticated and has all these bells and whistles, and then in the end, it's just useless.

Lyric mostly associated teaching modelling with her methods courses. Her emphasis indicates two key core beliefs: (1) that instruction of modelling typically happens in a special course and (2) modelling instruction is not common in undergraduate classes. Since modelling instruction typically happens in a methods course, it is not common for other classes to focus on aspects of modelling. These core beliefs were Lyric's perceptions of the state of the undergraduate geology program; she was adamant that modelling is important for all students to learn. She voiced ambition to add more modelling instruction into her undergraduate classes. However, she felt the

mathematical preparation of her students prevented her. Like Haven and Quinn, she stated that she reserved discussing the mathematics behind the models for her graduate classes. She was clear that she included highly structured and simple models only in her junior and senior level undergraduate courses:

I would. I would love to. I would love to [teach modelling earlier in the program].

I would love for them to come in very prepared mathematically. I would love to show them not only the simple ... I do show them the simple models, but I'd like to show them more sophisticated models, and prepare them even better for the working world, or prepare them better for graduate school. I would love it. I really would. But you just can't. You just can't (Lyric, 208).

Because of the constraint of students' level of preparedness has on the mathematics that she teaches to her whole class, Lyric identified students interested in learning more and sought to broaden their understanding of mathematical modelling in preparation for graduate studies.

Cross-Case Synthesis and Discussion

In this section, we reflect on similarities and distinctions between the participants in our sample and findings previously reported in STEM education literature. The beliefs presented by Drakes (2012), Frejd and Bergsten (2018), and Gainsburg (2013) also appeared among the core beliefs of our participants, though not uniformly. Specifically, the idea that *models capture and describe relationships between variables abstracted from a real-world phenomenon*, showed up in a psychologist's, a geologist's, an anthropologist's, and an economist's core beliefs. This means that the important, salient, definition that models capture and describe relationships between variables was also present across multiple peripheral STEM disciplines. The idea that *modelling is a human activity inherently involving compromise* was also present in an anthropologist's

core beliefs. This indicates that beliefs about modelling present in the literature on STEM instructors are also present in peripheral STEM disciplines. However, beliefs such as *modelling is used to understand a real-world phenomenon*, *modelling is the same as problem solving*, or *modelling is setting up and validating equations* were not represented in our participants' core beliefs. While we cannot conclude that the participants did not hold these beliefs, our methods support the claim that they are not participants' most salient beliefs. We speculate there may be some ties between participants' beliefs and the idea that social sciences engage in the statistical study of theoretical constructs regarding human behaviour rather than seemingly inviolable physical laws, as Riley implied. Gainsburg's (2013) results indicated that instructors of modelling tend not to mention computer modelling (a theoretical model that underlies some software, or a specific representation of an object made in computer-aided design software), but professional engineers use computer modelling and modelling interchangeably. Similarly, none of our participants explicitly discussed computer modelling, and 6 of 10 discussed some form of statistical modelling (a statistical model is an equation derived from a statistical process).

The literature suggests instructors hold differing ideas about the role of mathematics, and thus of modelling, in science, technology, and engineering (STE) courses. As discussed in the review of literature, the two big ideas about the role of mathematics in STE are that of inseparability (STE cannot be taught without also teaching mathematics) and isolation (STE and mathematics are taught in their own courses). Both sentiments were also found among the core beliefs of our participants. Karter (economist), and River (geologist), insisted that mathematics was inseparable from their courses' content. In contrast, Phoenix (anthropologist), talked about mathematics as a tool to be taught in another class, like an economics analysis class.

We note that differing conceptions of STEM integration do not seem to originate in the participants' disciplines. The contrasts seem to be rooted in the instructors' salient experiences with mathematics and the nature of modelling in their professional lives and teaching. For example, Karter (economist) told a compelling story of studying mathematics in his youth and explicated many examples of using modelling in his career. In contrast, Phoenix (anthropologist) did not share any salient experiences with modelling in his research or while teaching. Riley (anthropologist), Karter (economist), and River (geologist) implied that mathematical applications were a critical component for their course content. Riley gave many examples of teaching mathematical models, from carbon dating to predicting human behaviour across circumstances throughout prehistory. However, Riley also stated that he would steer away from discussing the mathematics behind these models to avoid scaring his students. This sentiment is likely tied to Riley's strong negative experiences with mathematics in his youth.

Previous research about the epistemological beliefs teachers and students hold about the nature of mathematics states that these beliefs can be categorized into four principal orientations (Felbrich et al., 2008; Tossavainen et al., 2017).. Someone with an application-related orientation would view mathematics as a science that could be used to solve problems relevant to society. Someone with a process-related orientation would view mathematics as a science of problem-solving processes to discover structure and regularities. Someone with a formalism-related orientation would view mathematics deduction-based science build from axioms. Someone with a scheme-related orientation would view mathematics as a collection of formulae and procedures (Felbrish et al., 2008). Some of the core beliefs identified among our participants match these orientations. For example, the application-related orientation and the process-related orientation can be observed among the core beliefs *models are used for prediction*,

description, or explanation and mathematics is a tool, respectively. Based on our findings and comparison with the literature, we infer that some beliefs about the nature of mathematics, and modelling, are not unique to those who teach or study mathematics, they can also be found in users of mathematics.

Gandhi-Lee et al. (2015) and Faulkner and Herman (2016) showcased the weight STEM instructors place on their students' mathematical proficiency. Gandhi-Lee et al. (2015)'s participants talked about mathematics as a roadblock, and how algebra was the minimum for mathematical preparedness. Six of our participants held core beliefs surrounding the idea that mathematical preparedness was a roadblock to implementing modelling tasks in the classroom.

However, we observed a level of idiosyncrasy in how each participant operationalized preparedness. Predictably, some instructors operationalized mathematical preparedness to mean algebraic fluency or proficiency with calculus. For example, Quinn (psychologist), explained that he had to scale back the difficulty of the mathematical analysis in an in-class experiment.

I, over the years, I still do that in the class but I've kind of scaled back the complexity and difficulty of the exercises. I've found that I just needed to and the main reason... Where a math problem that I thought should be pretty simple if you've just taken college level, I don't know, algebra for example. It wasn't anything too crazy that I gave the students. Even then some students had difficulty with it. Not all, some students did just great but I felt that I needed to kind of scale back the complexity of those problems.

Haven (psychologist) suggested that mathematical preparedness meant fluency with graphical representations and their meanings. She explained that graphical expressions were most important for her students because specifics about what

statistical models to run could be looked up later. She recounted a conversation with one of her graduate students who was having difficulty labelling the scatter plot illustrating their statistical hypothesis. While recalling this conversation, Haven lamented that students generally were not skilled with graphical representations.

If you can't figure out what's the label on our scatter plot, if you can't figure out what the Y and X axis should be labelled, take a step back and think through what you're doing. I guess that's not an issue of what buttons to click or what the test is called. I was like, 'I can tell you what the test is called.' Once you get that to me, that's the work I want to see you doing is thinking through graphically how to depict the data. Once you do that work, then you also know what to Google.

Both Haven and Quinn taught STEM majors in a psychology department. However, their operationalizations of mathematical preparedness were dissimilar. This is partially due to the courses they teach. Quinn's classes lent themselves more to mathematical exploration than Haven's. The dissimilarity may also be rooted in their experiential backgrounds. Both have experience studying mathematics as students themselves, but the types of mathematics were very different. Haven spoke mostly of studying mathematics in her statistics and methods courses, while Quinn studied mathematics and physics at both the undergraduate and graduate level. Overall, there was broad consensus that mathematics was a common roadblock for students in their field, echoing sentiments of engineering faculty (Tague et al., 2013). However, across the sample, there was no clear pattern of what was meant by mathematical preparedness based on STEM field or mathematical content.

Perhaps a consequence of the weight STEM instructors place on mathematical preparedness, we observed a connection between STEM instructors' perceptions of students as doers of mathematics and the place modelling has in undergraduate

students' course work. As reported above, most (6 of 10) of our participants held the core belief that students are not mathematically prepared enough to have productive discussions about modelling in the classroom. Other core beliefs that modelling instruction is not common in undergraduate classes (5 of 10) and/or modelling instruction is for graduate or potential graduate students followed suit (6 of 10). Participants holding these beliefs described the relationship as follows: typical STEM undergraduates are not mathematically prepared for whole-class discussions on modelling, so participants concluded they could not add modelling to their course work. Consequently, modelling is not common in undergraduate classes. However, if a student is vocal about going to graduate school or is in graduate school, then the participant will provide instruction on modelling. Our participants expressed sadness and frustration that this was the case. In contrast to how mathematics instructors lament that there is not enough time in a course to add modelling and applications (Schmidt, 2010) some of our participants lamented that the modelling they wished to teach their students was not compatible with the students' existing mathematical skills.

Limitations

We note that validity of a research study is not guaranteed by following a procedure (Creswell, 2007) and so we were sensitive to methodological choices and reporting choices that could augment credibility, validity, and reliability. First, we followed the common practice of recording and transcribing interviews to preserve the verbatim words participants used to express their stories. This enabled us to report descriptions of our participants' experiences as richly as they told their own stories (Tracy, 2010). The plot development technique allowed us to explore alternative interpretations of the data. Finally, asking participants directly about their beliefs tends to be reactive, meaning that participants may answer what they think the interviewer

wants to hear or what they think a socially acceptable response might be. Our protocol instead asked them to relate salient-to-them stories from their lived experiences, a choice that would minimize reactivity.

Conclusions

Our study builds on and extends a synthesis of literature describing beliefs held by STEM instructors about the role of modelling in the classroom through documenting perspectives of instructors from STEM disciplines not typically included in the literature. This work was necessary as more disciplines on the periphery of STEM increasingly rely on mathematics and statistics to solve problems within their disciplines.

Overall, there were sentiments held in common about modelling and modelling instruction shared among these peripheral STEM instructors and central STEM instructors, such as mathematics knowledge being a barrier to implementing modelling in the classroom. However, what is meant as mathematical preparedness seems to be idiosyncratic to the individual professor and partially dependent upon the specific course content. This implies that discipline-level analysis may not be an appropriate grain size for investigating the mathematical barriers students face. Future research endeavours to uncover instructors' beliefs and practices about modelling in STEM may wish to be cautious when constituting *field* as an independent variable because variation in instructional decisions may be precipitated by idiosyncrasies of the instructor's beliefs. Said differently, disciplines like anthropology, psychology, and geology (among others) are very broad in terms of the methods of inquiry they permit and the research questions they ask. Treating them as monolithic—as a researcher would need to do in order to constitute them as an independent variable—would wash out these subtleties. Instead, we suggest surveying participants about their prior (lived) experiences with

mathematics, statistics, and modelling to constitute independent variables in future studies of instructors' beliefs about the role of mathematics and mathematical modelling in their respective disciplines. Especially in quantitative or mixed-methods research, an aggregate measure of prior experiences may be a more accurate predictor of disposition towards modelling. Additionally, beliefs about mathematics' role in instruction was also as mixed as it was in literature focused on central STEM disciplines (Holmberg & Bernhard, 2017; Kaiser, 2017; Nathan et al., 2010). This variability in instructors' beliefs about mathematics' role in instruction must be accounted for in future work on persuading STEM instructors modelling is a doable and worthwhile endeavour, but we do not recommend accounting for it at a field-based level.

Our study demonstrates some ways in which instructors' lived experiences lead them to develop beliefs about which students are capable of modelling instruction in undergraduate coursework using the method of narrative analysis. While this methodology does not allow us to make inferences about how participants' beliefs mutually impact one another, it has allowed us to make conjectures about the genesis of the participants' most salient beliefs.

Our participants repeatedly indicated they would skip opportunities for mathematical modelling in order to mitigate the reactions they anticipated students would have, such as frustration and experiencing failure. We conjecture that STEM instructors who empathize with that frustration reserve mathematical modelling for the most promising students while those who had many positive experiences with mathematics feel that learning to model is a worthwhile struggle for the students. These issues are salient in the periphery of STEM and come up just as strongly as in central STEM courses. From an equity perspective, we would encourage future work surveying STEM professors, from both central and peripheral disciplines, to explore what

indicators professors attend to when identifying students who are ‘interested’ or ‘prepared’ for supplemental modelling instruction. Further, future work might consider exploring the other pillars from Schoenfeld’s (2011) framework in relation to the decisions about whether to incorporate modelling and to what extent.

In general, educational researchers have been stressing the importance of integrating mathematical modelling into STEM curricula. One part of convincing STEM instructors to incorporate more modelling in their courses is developing tasks that are doable and worthwhile. Our study makes clear there is more work to be done in these peripheral STEM disciplines. While our study expands the applicability and generalizability of the current literature, we recommend a concerted effort by researchers of modelling to properly account for domains in the periphery of STEM that are trending mathematically to create a comprehensive picture of modelling at the post-secondary level. For example, future research could be done to explore the extent to which current educational perspectives on mathematical modelling, disseminated in the mathematics education literature (e.g., Kaiser, 2017), are compatible with the views of modelling held by members of peripheral STEM disciplines.

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Table 1 Participants' core beliefs about modelling and modelling instruction

[illegible]

	Participant	Emerson	Karter	Phoenix	Riley	Haven	Sage	Quinn	Parker	River	Lyric
	Field	Econ	Econ	Anthro	Anthro	Psych	Psych	Psych	Geo	Geo	Geo
	MM instruction is not common in undergraduate classes	X		X		X		X			X
Nature of MM instruction	MM instruction is carefully planned, uses simple mathematical ideas, and focuses on understanding concepts				X	X	X	X			X
The instructor's relationship with mathematics/modelling	Instructor wants to do more MM instruction	X									X
	Instructor's experience with MM plays a role in MM instruction		X							X	
	Instructor's experience with MM does not play a role in MM instruction						X				

	Participant	Emerson	Karter	Phoenix	Riley	Haven	Sage	Quinn	Parker	River	Lyric
	Field	Econ	Econ	Anthro	Anthro	Psych	Psych	Psych	Geo	Geo	Geo
	Faculty are not mathematically inclined				X						
The student's relationship with mathematics	Students are not mathematically inclined				X	X				X	
	Students are not mathematically prepared	X				X		X	X	X	X
What a model is used for	Models are used for prediction										X
	Models are used for description/ explanation	X						X			
Characteristics of a model and the modelling process	Models must be complex systems of equations	X									
	Models do not need to be complex									X	
	Modelling is quantification				X					X	

	Participant	Emerson	Karter	Phoenix	Riley	Haven	Sage	Quinn	Parker	River	Lyric
	Field	Econ	Econ	Anthro	Anthro	Psych	Psych	Psych	Geo	Geo	Geo
	Modelling is from first principles									X	
	Modelling is a statistical process		X	X	X	X	X		X		
	Qualitative aspects of modelling are important					X					X
	Modelling has limitations				X						
Field's relationship with modelling/mathematics	Modelling is important to the field	X						X			
	Modelling is not important to the field			X					X		
	Mathematics is a tool for the field		X								

Table 2 Four most-commonly held core beliefs among the 10 peripheral STEM

instructors

Core Belief	Description
Students are not mathematically prepared	Participant states that their students are not mathematically prepared to have discussions about modelling
Instruction is not common in undergraduate classes	Participant states that modelling instruction does not happen (or happens infrequently) in undergraduate classes.
Instruction on modelling/ or that uses mathematics is planned, uses simple math, and focused on understanding concepts	Participant states that modelling instruction that occurs in their class is typically simple (from their perspective), is meticulously planned, and/or is focused on understanding concepts (e.g., why a certain technique is appropriate, or how to interpret the findings in the real-world)
Instruction is for graduate students or potential graduate students	Participants states that modelling instruction occurs in graduate school, or modelling instruction is given to students who aim to go to graduate school.

Figure 1

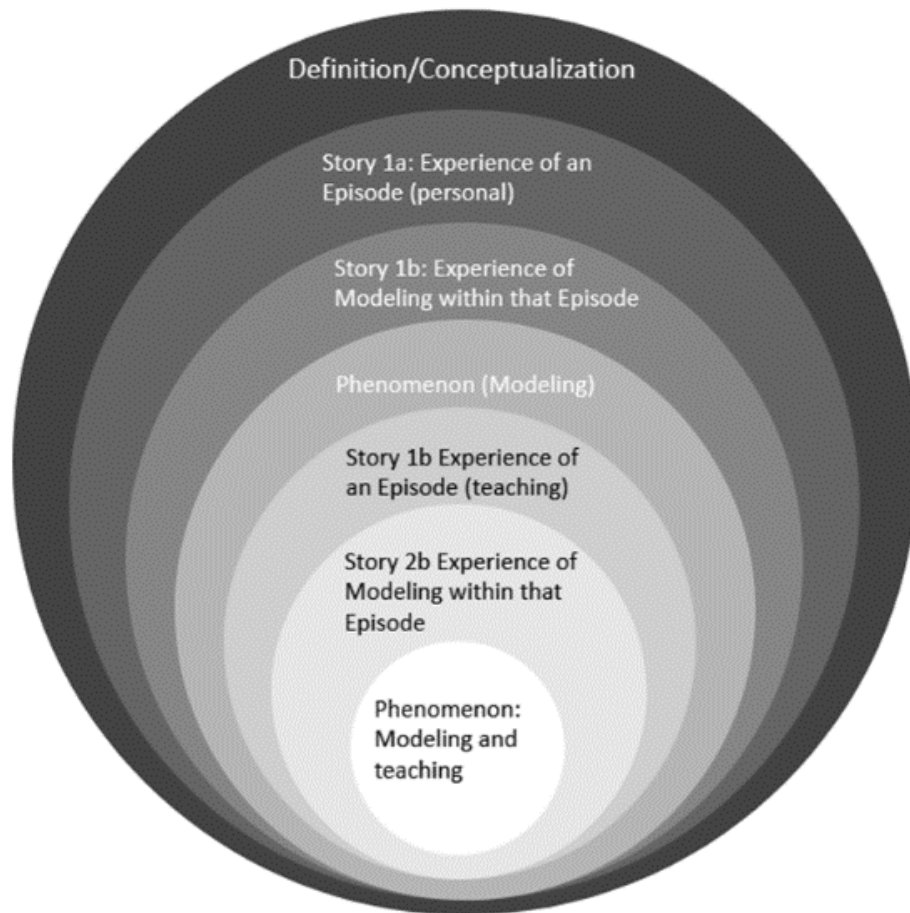


Figure 2

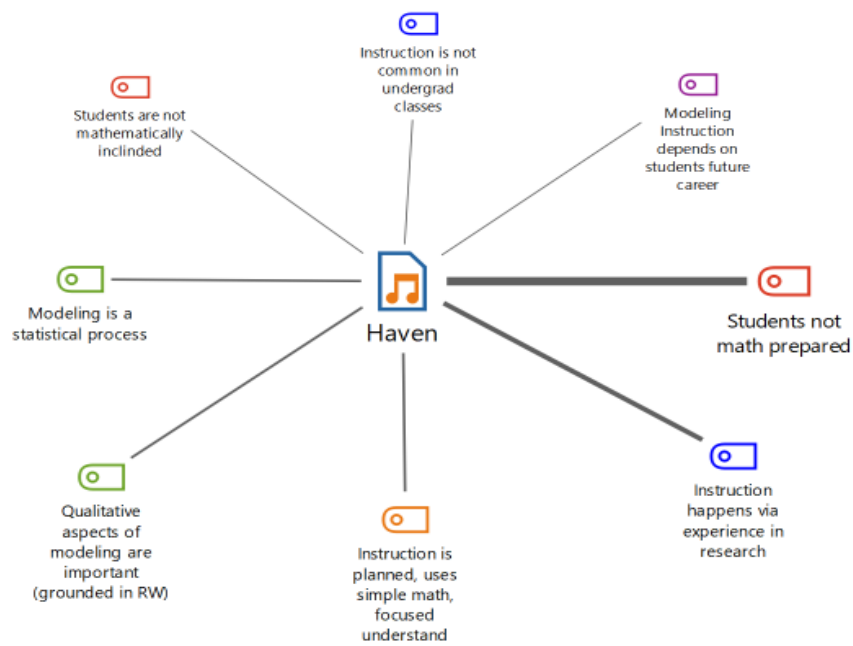


Figure 3

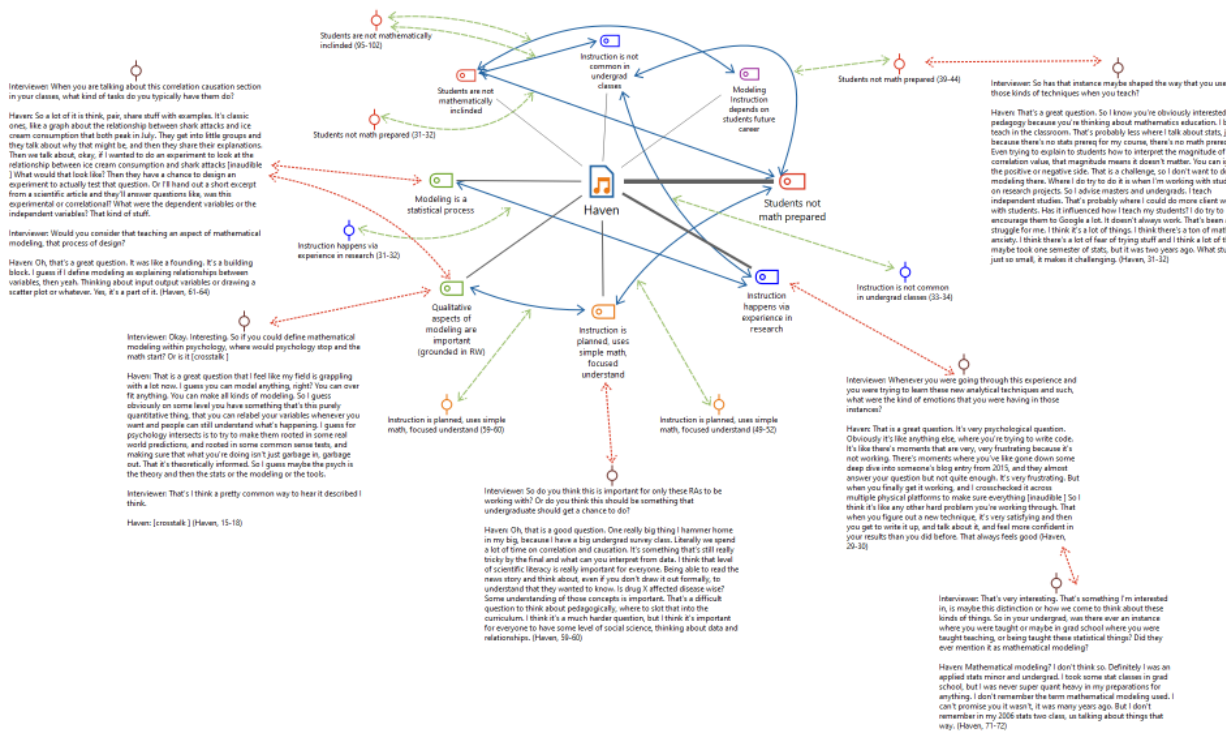


Figure 4

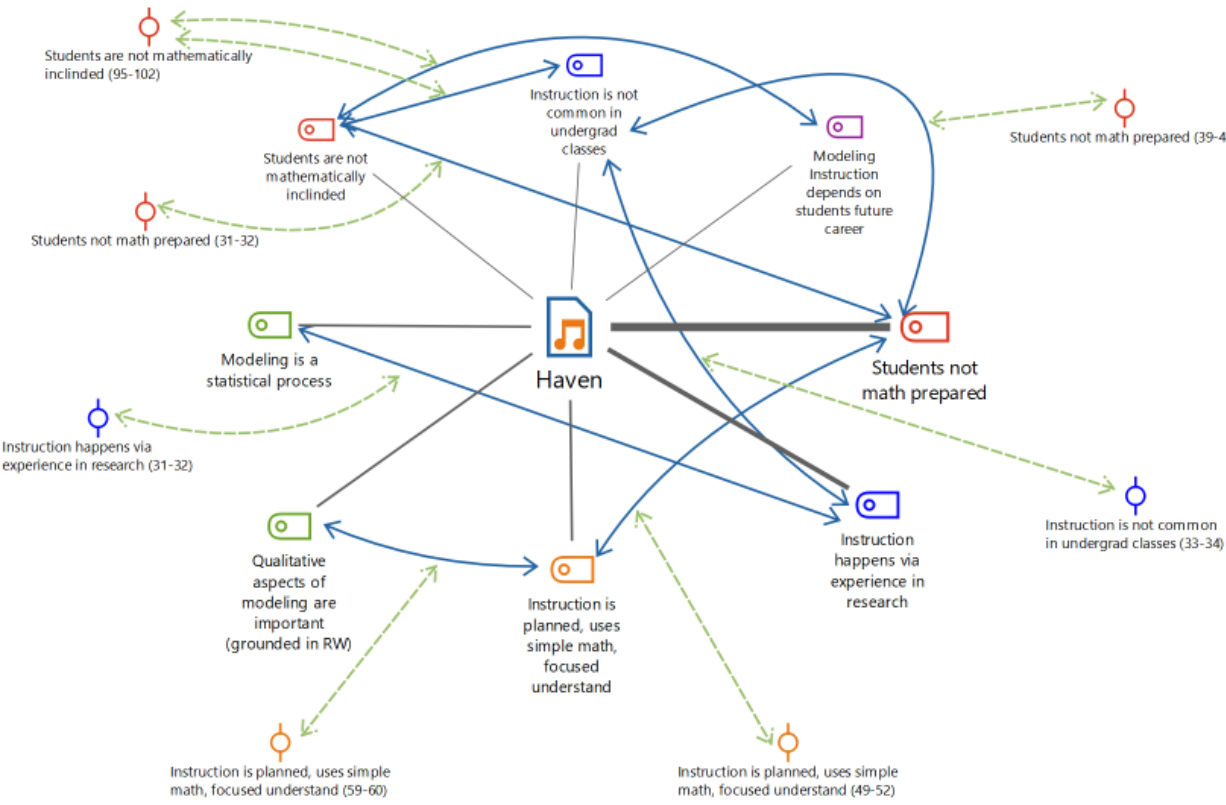


Figure 1 Illustration of *funnelling* the guiding structure for episodic narrative interviews (Mueller, 2019)

Figure 2 Building core beliefs for Haven in MaxQDA

Figure 3 Visual sample of emplotment analysis for Haven, from MaxQDA

Figure 4 Building a hypothesized plot outline for Haven in MaxQDA.

Appendix

Interview Protocol

- Introduction
 - What is your primary field of research at <university>?
 - What is courses do you typically teach?
- Definition/Conceptualization (modelling in general)
 - Can you tell me what the phrase mathematical model means to you?
 - If they provide a description, then ‘What are the big mathematical models used in your field?’
 - Can you tell me what the phrase ‘mathematical modelling’ means to you?
 - How would you define mathematical modelling?
 - Can you identify where your <science> stops and the math begins?
 - What is meant by <real world/everyday> and <math world> (use interviewee’s vocabulary here)
 - How do you think mathematical modelling is discussed in your field of research?
 - Is mathematical modelling a topic that is explicitly spoken about?
 - For example, are there journals that discuss new models?
- Story 1a: Experience of an Episode (about their experience with mathematical modelling) (‘The important goal is to help the participant vividly recollect an episode or bounded situation in which they were likely to have also experienced the phenomenon of interest.’ (Mueller, 2019, p. 7))
 - Can you please tell me a story about a time in which you used mathematics in your discipline? This could be a time you tried to apply mathematics in your own research or your industry job (if applicable)? <allow time to think>
 - Could you please include more information in your story about:
 - The environment?
 - The people involved (other faculty, research assistants, ect.)?
 - What question was the mathematics supposed to answer?
 - How did you determine to use that mathematics?
- Story 2a: Experience of Mathematical Modelling within that Episode (‘tell another story, this time about his or her experience of the phenomenon within the context of the episode.’ Mueller, 2019, p. 7)

- Could you expand more on your use of mathematical modelling within the story you just told? <allow time to think>
 - Could you please include more information in your story about:
 - If you consider your previous story as an attempt to mathematically model the problem? Why/Why not? (some people say that statistical like HLT)
 - Would your field/ colleagues/industry contacts consider instance of mathematical modelling? Why/Why not?
 - Is there any disagreement in your field about the use of mathematical modelling?
 - Is there a distinct sub-field that tends to use it more often, or exclusively?
 - Would you consider your attempt to use mathematical modelling a success?
 - If they say it was successful, what made the attempt to use mathematical modelling a success?
 - If they say it was not successful, why do you think this attempt was unsuccessful?
 - What emotions did you feel during your story?
 - What about the experience made you feel <emotions they identified>?
 - How has this instance shaped the way you treat mathematics in your research, in your industry job (if applicable), in your course preparation?
- Definition/Conceptualization (modelling while teaching)
 - Which courses do you teach, if any, have applications of mathematics in the course work?
 - How does mathematical modelling fit into those classes as a whole?
 - How does mathematical modelling fit into your student's major work?
 - Does it vary depending on specific programs within your department?
 - What other courses are required in the teaching of mathematical modelling to your students?
- Story 1b: Experience of an Episode (about teaching mathematical modelling)
 - Can you please tell me as story about a time you taught your favorite application of mathematics in your favorite class course? <allow time to think>
 - Could you please include more information in your story about:
 - The environment
 - The students involved

- How did this application come up? (planned or spontaneous?)
 - Other teachers involved (for example, TAs)
 - What mathematics were involved?
 - What was the mathematics intended to be used for?
- Story 2b: Experience of Mathematical Modelling within that Episode
 - Within the time you taught mathematics in your class, can you please tell me a story about a time you taught mathematical modelling? <allow time to think>
 - Could you please include more information in your story about:
 - Do you consider the time you taught mathematics in your class as teaching some aspect of mathematical modelling?
 - If yes, what aspects of mathematical modelling were you teaching?
 - If no, why do you not consider this instance as teaching some aspect of mathematical modelling?
 - Where your students prepared enough to engage in the mathematical modelling tasks you prepared for class?
 - If students knew the math they needed for <science>, would you be able to do modelling tasks?
 - Is this a valuable experience for your students? Why/why not?
- Closure
 - What made you go into your field?
 - You told me a lot about modelling in teaching and research, is there anything else connected to those stories that comes to mind?
 - Is there anything you would like to change about your stories?