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Building STEM in Schools: An Australian Cross-case Analysis

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ABSTRACT: The Principals as STEM Leaders (PASL) project was an Australian Government-funded national research and professional learning programme for principals, aimed at building STEM leadership capacity. The project involved cluster-based delivery of six learning modules and generation of case studies outlining schools' different approaches to STEM education and STEM leadership. This article analyses factors contributing to the development of four contrasting schools' STEM profiles, identifying the unique approaches and leadership strategies each adopted in designing STEM curriculum for meeting the learning needs of their diverse students. It positions these schools' endeavours within the broader PASL professional learning programme, adding to the limited body of empirical work detailing different approaches schools take to the "STEM challenge," which, for most, presents a disruptive innovation to traditional curriculum and structures. The vital role of school leaders in communicating a clear, evidence-based vision for STEM and also "walking the talk" and being highly engaged in STEM programmes, was a common feature across the cases. This built relational trust, and a strong whole-of-school commitment to and understanding of STEM, to some extent mitigating the challenges of rigid curriculum and external assessment requirements. The study highlights the complex interaction of professional learning, leadership, curriculum design, pedagogy, and school culture in establishing innovative STEM programmes in schools.

Keywords: Principal, STEM, Leadership, Curriculum, Professional learning

1. Introduction

The Principals as STEM Leaders (PASL, the scope of this article precludes detailing this project in depth. Detailed information can be found at https://www.utas.edu.au/education/research/research-groups/maths-education/pasl/pasl) project was a three-year, Australian government-funded initiative launched in 2017, to "strengthen the foundation for greater participation and engagement, and ultimately better learning outcomes, in STEM subjects" (Birmingham, 2017, p. 1). PASL involved over 150 principals, and focused on building school leadership in STEM by "develop(ing) and pilot(ing) new approaches to support principals to provide high quality STEM leadership in schools" (DESE, 2018, np). The project was led by the University of Tasmania, with collaborators from six other universities. PASL was responsible for delivering professional learning (PL) and associated initiatives in each Australian state, through bespoke modules designed to build principals' knowledge and professional leadership in STEM capability dimensions (Beswick, Fraser & Geiger, 2017). The dimensions were STEM discipline and integrated knowledge and practices; contexts for STEM teaching and learning; STEM-supportive dispositions; STEM tools and resources (digital and non-digital), and critical orientation towards STEM leadership. The modules were designed for delivery face-to-face, online, and in blended format, and were supported by research that explored current STEM teaching and leadership practices, and the influence of the professional learning on school programmes. Aligned with the learning modules were four school case studies, developed to "identify the leadership and teaching practices in STEM that are currently working well with the aim of rolling these practices out more broadly in our classrooms" (Birmingham, 2017, p. 1). Case studies informed the PL and the revision of modules between iterations, providing practical illustration of how introduced concepts could be implemented in schools, and their related leadership practices. The four case studies reflected a range of schools from different states, each forging their own pathways in meeting the STEM subject requirements of local and national curricula (e.g., ACARA, 2019; NESA, 2019).

This article analyses the approach each case study school took towards building students' STEM knowledge and capabilities, and supporting overall STEM literacy development. Valuable knowledge was generated that highlighted the complex interaction between professional learning, leadership, curriculum, pedagogy and contextual factors, in establishing each school's unique STEM profile. For that reason this article does not advocate a singular approach to STEM or compare one school's efforts as being better or worse than others. Furthermore, it adopts a broad perspective of STEM education as both separate-subject based, and "a crossdisciplinary approach to teaching that increases student interest in STEM-related fields and improves students' problem-solving and critical analysis skills." (ACARA, 2016, p. 4). In Australia, while some schools' STEM curricula may engage advanced technology, it is not a necessary requirement. Indeed, this perspective is consistent with literature that suggests there are many different approaches to STEM, each one reflecting different priorities, resources and constraints (e.g., Falloon et al., 2020; Honey et al., 2014). The analysis revealed insights into the schools' approaches, and how each developed their STEM programmes reflecting different emphases on professional learning, leadership, curriculum, pedagogy, and contextual factors - such as access to digital and community resources. Findings add to the limited research base concerning how schools in different contexts address the challenge of designing and sustaining STEM programmes, which can present considerable disruption to existing curriculum, pedagogy and organisational systems (Asghar et al., 2012; Zollman, 2012). It is anticipated these outcomes will benefit other schools planning their STEM trajectories.

2. Research questions

Data were analysed responding to these questions:

- What factors influenced the development of STEM education programmes in four Australian schools?
- What can be learnt from these schools about the complexity of establishing effective STEM education programmes?

3. A review of literature

3.1. Understandings of STEM and its relevance to education

Emerging in the 1990s from the early work of U.S National Science Foundation (English, 2016), the term "STEM" simply refers to the subject disciplines of Science, Technology, Engineering and Mathematics. However, their combination in the acronym STEM "was a strategic decision made by scientists, technologists, engineers and mathematicians to combine forces and create a stronger political voice" (STEM Task Force, 2014, p. 9), and also acknowledges the interdependence of the disciplines in making joint contributions to solving complex problems. Furthermore, the development of STEM capabilities is seen worldwide as a priority for supporting economic goals, particularly in knowledge-based economies. In Australia, the need to attract greater numbers into STEM careers is viewed as essential, "if the future workforce is to maintain and grow the reputation of Australia at the forefront of scientific knowledge and expertise" (Edwards et al., 2015, p.1). Beyond workplace readiness, the importance of improving 'STEM literacy' has been aligned with the development of essential skills, competencies, and dispositions needed to function effectively and productively in rapidly-changing future environments (English, 2016). These skills include critical and creative thinking, solving complex and ill-structured problems, autonomy, collaboration, and a growth mindset. Such capabilities are also viewed positively by employers, who identify employees' lack of interpersonal skills, critical thinking and continuous learning engagement, as major workplace challenges (Deloitte Access Economics, 2014). Increasingly, governments and employers are looking to education to improve the STEM performance of economies and businesses, through more engaging and authentic curricula that attract more young people to STEM study and careers.

3.2. STEM education

Despite acceptance and understanding of the acronym STEM, there is limited agreement on how teaching and learning in STEM should be approached in schools (Holmlund, Lesseig & Slavit, 2018). Generally, STEM is still defined by its separate disciplines, and is represented as such in official curriculum statements (e.g., Australian Curriculum, Assessment and Reporting Authority, 2015). While curriculum authorities seek improved STEM instruction, debate persists about if and how the STEM disciplines should be integrated into learning programmes, and the curriculum, pedagogical and organisational structures that best support this. While different approaches to STEM education have been identified (e.g., Falloon et al. 2020; Vasquez, 2014), interdisciplinary models are seen as the most effective (e.g., Bybee, 2010; LaForce et al., 2014; Zollman, 2012). In these, students construct and apply STEM knowledge and skills by developing or modelling solutions to "real world"' problems, needs or opportunities, often using problem or project-based learning models aligned with design thinking principles. However, while these approaches may enhance and make STEM knowledge more relevant to students, they present a significant challenge to prevailing single subject curriculum and assessment methods (Zeidler, 2016). Interdisciplinary STEM necessitates teaching across disciplines using strategies that support knowledge integration in authentic tasks, often utilising group, cooperative, or collaborative organisational structures. Such methods also demand a rethink of conventional assessment approaches, that traditionally prioritise individual over collective contribution and performance. Additionally, interdisciplinary project and problem-based structures are often seen as incompatible with secondary schools' existing emphases on discrete subject blocks. In many countries, these challenges are compounded by the absence of a STEM curriculum with system-level guidelines for planning and teaching. As Holmlund et al. (2018) points out, "without some shared understandings across a system, it is difficult to design and implement curriculum and instruction to promote successful STEM learning for all students" (p. 2). While some emerging examples detail schools' successful efforts to transition to alternative structures (e.g., Sleap, 2019), these are rare.

3.3. School leadership and STEM

Significant research highlights the importance of leadership to implementing changes and innovations in schools (e.g., Fullan, 2003; Minckler, 2014). Cohen et al. (2009) point to two factors that can aid or hinder the adoption of innovations like interdisciplinary STEM - namely school climate, and school culture. According to Cohen et al. (2009) climate reflects "the quality and character of school life, and reflect(s) norms, goals, values interpersonal relationships, teaching and learning practices, and organizational structures" (p. 180). It influences the day-to-day function of the school, establishing the 'tone and feel' of the school environment. Studies indicate a positive school climate improves teachers' engagement and performance, builds morale, and enhances student achievement (e.g., Donaldson, 2008). For Schein (2004), culture is established over time, and defined by the accepted ways in which the organisation operates and solves its problems. Put simply, culture defines how we do things around here, and is powerful when inducting new staff in an organisation "as to the correct way you perceive, think and feel in relation to (those) problems" (Schein, 2004, p. 17). Drago-Severson (2012) comments that over time school climate can influence culture, through leadership that promotes growth by providing opportunities for staff to embrace new initiatives and innovations.

Studies reveal that leadership is fundamental to the success of school STEM initiatives (e.g., Ford, 2017; Likourezos et al., 2020). Ford's cross-case analysis of the leadership practices in four STEM-focused high schools highlights the value of distributed and transformational approaches that empower individuals and groups within and external to the school to lead innovative, STEM-focused change. These approaches "inspired both teachers and students, raised the collective capacity of the school, provided leadership opportunities for teachers, engaged the entire school community, supported positive school culture and values, and addressed the needs of students underrepresented in STEM" (Ford, 2017, p. 198). In all schools, the work of principals in building positive change climates was critical to STEM development. Principals achieved this through securing commitment to a coherent STEM vision, fostering relational trust, strategic management of professional capital, establishing STEM-supportive networks beyond the school, and facilitating access to resources, infrastructure, and appropriate professional development.

4. Conceptual framework

There are multiple ways schools can approach the "STEM challenge," each involving pragmatic judgements about school climate and culture, readiness and support for STEM curriculum, resourcing, and teacher capability (Falloon et al., 2020). A flexible conceptual "lens" and accompanying methodology was therefore needed to accommodate the different approaches the four case study schools took to developing their STEM programmes. To support this, the OECD's (2013) generic learning environment model was used to understand the interacting elements that influenced each school's STEM trajectory. Figure 1 depicts the key elements of the model which interpret a learning environment as "a holistic ecosystem that functions over time and in contexts, and includes the activities and outcomes of learning" (OECD, 2013, p. 23). For analysing data from this study, elements of the model were interpreted into these code categories:

Organisation(al): Leadership of STEM, School context and culture;
Content: STEM curriculum;
Learners: (students), STEM outcomes;
Pedagogy: STEM pedagogy;
Educators (teachers, principals), School context and culture, Leadership of STEM;
Resources (material and non-material), School culture and context, STEM curriculum, Leadership of STEM.

Of note is that some code categories appear in multiple elements. This resulted from evidence in data of, for example, Leadership of STEM, being relevant to more than one element. That is, data indicated leadership as particularly important in Organisational, Resourcing, and Educator support and decision-making, and to a lesser extent in other elements, such as Content (STEM curriculum). Therefore, to support more precise reporting and discussion of data, the context-specific categories were used in place of the broader OECD elements in the analysis framework (see Appendix C). The interacting and overlapping nature of the code categories and their relationship with elements of the OECD model, is further discussed in the final section.

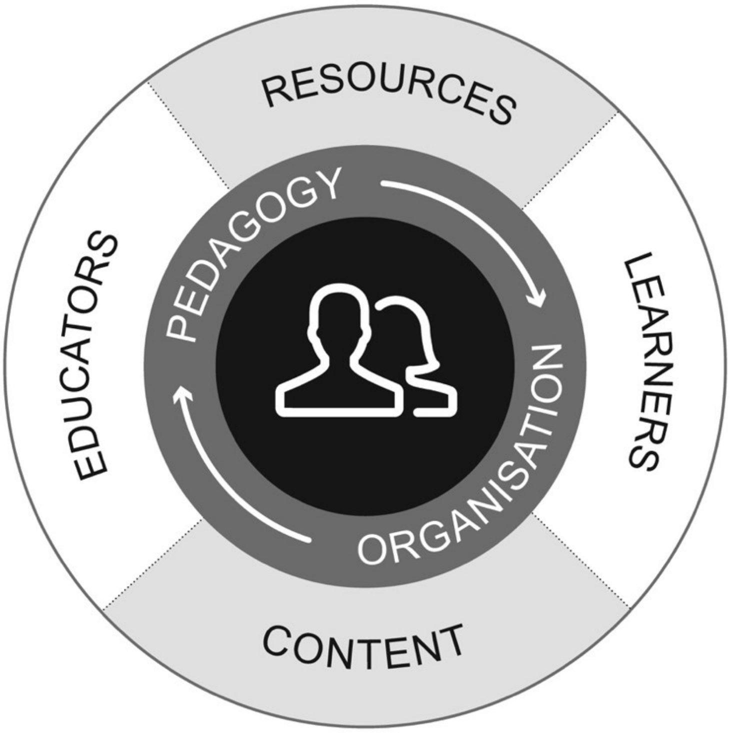

Figure 1. The OECD (2013) Learning Environment Model (See https://read.oecd-ilibrary.org/education/innovative-learning-environments_9789264203488-en#page27)

5. Research design

5.1. The case study schools

The schools were purposively selected as offering effective STEM programmes, and identified through education system and research network nominations as having strong commitment to STEM education. School selection broadly aligned with the OECD's approach, where cases were "chosen based on an understanding of 'innovation' in their own context… [which] left the nature and extent of innovation open to interpretation" (OECD, 2013, p. 25). Final selections ensured a balance of school profiles (location – city, rural/remote/regional), education systems (government, independent, religious) and types (coeducational, single sex, K-12, primary and secondary). Appendix A summarises deidentified participant and profile information for each school. Members of the research team gathered data from each site at different times across the project's lifecycle, using the methods outlined below.

5.2. Data methods and coding

Data were gathered via staff interviews (those with STEM leadership or teaching responsibility), student focus groups (students engaged in STEM programmes), and classroom observations. Interviews followed a standard protocol and question schedule. Data focuses are detailed and aligned with instruments, participants and number of items analysed, in Appendix B. Qualitative data were transcribed and coded using a hybrid method that combined inductive and template approaches to maintain fidelity, while providing a semantic structure for deeper analysis (Fereday & Muir-Cochrane, 2006). Transcripts were manually checked for accuracy and consistency, before a random selection was inductively coded to generate a draft primary and secondary theme template to be applied to all data. This was checked against the sample by a second author, and adjustments were made including conflating some primary codes to accommodate data that crossed over between categories, and refining coding decisions to better align with sub-categorisations. Five primary categories were agreed to: Leadership of STEM; STEM pedagogy; STEM curriculum; STEM outcomes; School context and culture. The subcategories were used to code data, as they provided a finer-grained "lens" supporting more accurate decisions. During analysis of the full dataset these were refined by adding, combining, and removing some subcategories, reflecting their close and at times overlapping association. A summary of the primary and subcategories, a description of each, and sample data is provided in Appendix C. Primary categories were defined as:

- Leadership of STEM: how STEM programmes were conceptualised (rationale and "vision"), leadership responsibility and teaching expectations, principal/teacher backgrounds and partnerships;
- STEM pedagogy: principals' and teachers' beliefs about how STEM should be taught;
- STEM curriculum: different interpretations of learning design and planning, and challenges to implementation;
- STEM outcomes: how learning is assessed, and indicators of beneficial outcomes from STEM programmes;
- School context and culture: climate, culture and environment reflecting support for STEM, and understanding of its role and importance to students' learning, social and work needs.

Coding followed a systematic process whereby data units aligned with each subcategory were identified using keywords/strings - samples of which are recorded in Appendix D. Units varied in length, with selections made based on the extent of evidence needed to support defensible decisions. In inductive coding, it is common to vary the length of coding units. Some units can be relatively short because the concept is clearly conveyed in a single sentence or clause, while others need to be longer where a participant is explaining something in greater depth. Illustrative longer excerpts are included in the discussion of findings, while shorter examples aligned with the subcategories are recorded in Appendix C.

5.3. Analysis

After coding against first and second-order themes using the template (Appendix C), data were enumerated to calculate frequencies associated with keywords, strings, and coded references. The research team revisited all coded references (ref.) and listed the commonly occurring keywords and strings related to each code. To determine the number of keywords and strings across the dataset, by using Boolean search functionality in Nvivo and entering all previously identified strings and keywords for each code in the one search box, it was possible to calculate frequencies against each code. A customised report generated the number of references associated with each code, as well as the number of words coded for each. A final variable was calculated to determine the average number of words per coded reference (total words coded divided by the number of coded references). These calculations are included in Appendix D, columns 4-8. This method revealed the emphasis given to different aspects of the schools' STEM developments, as discussed below. Longer data excerpts have been included in the discussion, where considered beneficial for illustrating participants' perspectives and priorities in greater detail.

6. Findings

Appendix D summarises how data were coded with respect to keywords and strings (columns 4 and 5), and coded references and words coded (columns 6-8). The keywords and strings variables reflect participants' choice of words when communicating perspectives (precision) and the range used across data (breadth). This approach enabled coding of data representative of broader concepts, rather than relying solely on exact word matches that may have missed more nuanced descriptions. The number of coded references (column 6) records the prevalence of data aligned with each subcategory, indicating some concepts attracted greater attention than others. For example, the fewer coded references for Professional Background (25) were almost entirely linked to the first interview question, while participants revisited Curriculum Planning (145) multiple times across several questions. The total words coded and average number of words per coded reference (columns 7 and 8) thus helps to better reveal the depth of detail in responses, particularly in subcategories where there were fewer strings and coded references but higher total and average numbers of coded words. For example, in the subcategory STEM Vision there were few strings (9) and coded references (54) but relatively more words coded (4685), thus yielding the highest average number of words per coded reference (91.86). Larger numbers of both total words coded and average number of words per coded reference typically indicated participants provided greater depth in their explanations and responses.

Figure 2 provides a side-by-side statistical representation of data in each primary category (i.e., collapsed subcategories) by number of strings present (column 5), total coded references (column 6), and average words per code (column 8). Except for STEM Curriculum and Leadership of STEM, all categories returned significantly more strings than coded references, typically reflecting multiple strings used to refer to each concept and greater breadth of detail or explanation. For example, in School Culture and Context, 955 strings were used in only 292 coded references. Participants' responses in this category were often broadly defined and referenced multiple examples. By illustration, responses in Resourcing for STEM often yielded multiple examples of STEM resources in a single coded reference, for example "... we have a lot of resources at our disposal. We have an ideation lab - it's got a lot of laser cutters, 3D printers, tools we can use, materials if we don't want to buy everything ourselves" (School 1, Student 3). Other categories showed only minor variation, suggesting participants were less inclined to elaborate on responses. Leadership of STEM, for example, registered 265 strings and 226 coded references, and in subcategories such as Beliefs about STEM, few examples or details were offered e.g., "I feel like a lot of the skills you develop in STEM can be applied in many other areas" (School 3, Student 1). Moreover, these subcategories often yielded instances where a perspective was expressed without clearly signposted keywords or phrases. For example, as one student commented, "...it's the problem solving… you look at something and you think it's going to be so straightforward… [but] you have to uncover so many layers, and it's like… it's calculated decisions every single time…" (School 3, Student 5). In such cases, coding had no associated keywords or strings. STEM Curriculum was the other category reflecting relative parity between keywords/strings and coded references, returning 603 strings and 583 coded references. The comparatively high number and close alignment of coded references and strings, and low average words per coded reference, suggests that although participants were keen to comment on STEM curriculum, typically their responses were brief. This coding method therefore provided some tentative indications of the understandings, priorities, interests and concerns guiding participants' STEM developments in their schools.

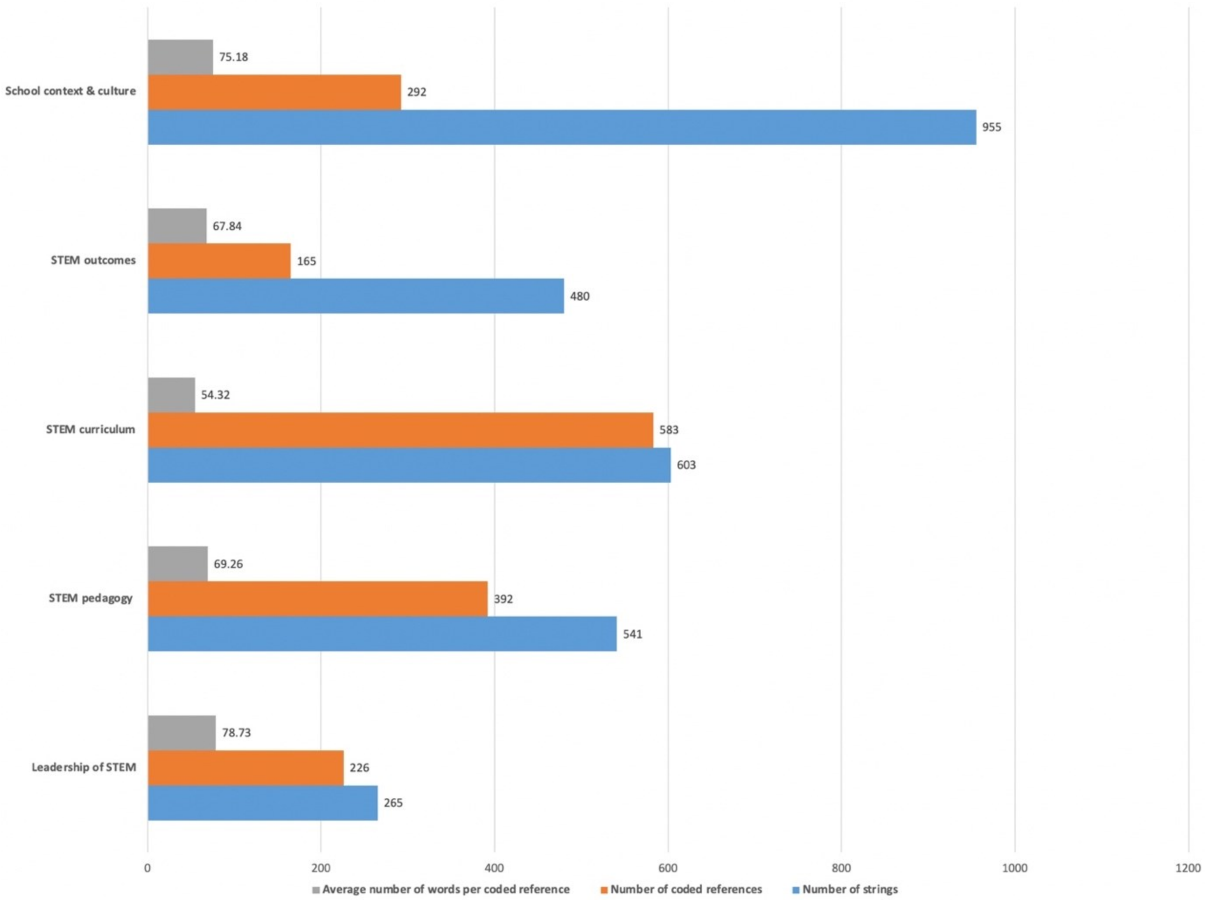

Figure 2. Side-by-side analysis: number of strings, coded references, and average words per coded reference

7. Discussion of findings

Responding to question 1, findings are discussed using the broad categories outlined in the OECD model. In this study, Organisational elements relate to Leadership of STEM and STEM-supportive school Culture and Climate;

Content and Pedagogy refer to STEM curriculum and approaches to teaching; Educators are the teachers and principals, Learners are the students, and Resources are the materials, equipment, infrastructure and professional learning supporting STEM programmes. In reporting data below, schools are denoted (S*n*), teachers (T*n*), principals (P) and students (St*n*).

7.1. Leadership of STEM

Data indicated some teachers and principals linked their professional background to their decision to pursue STEM in their schools (25 refs.), often reflecting a change of career from a STEM profession such as architecture, graphic design, or IT - to teaching in schools. Teachers' STEM industry experience was an asset in each school. As one teacher commented, having two ex-engineers on staff was like having "all the building blocks in place" (S3, T2). Several teachers with STEM leadership responsibility had non-STEM backgrounds - for example, as teachers of English and Geography. However, they considered it beneficial to further their disciplinary knowledge by looking for creative ways to integrate their discipline expertise with STEM. This also applied to two principals, with one commenting, "I don't come from a farming background … but I suppose my skills were in strategy, and so I'd been aware that really what I just needed was to support and to implement strategic approaches to (STEM) improvement" (S4, P).

Across all schools, staff and students were acutely aware of principals' expectations relating to STEM achievement (95 refs). The high string count (n = 112) for the Leadership of STEM category reflected the presence of keywords and phrases such as *they should*, *we have to*, and *it's important to*, which were used to reference STEM initiatives across the 12 strings mapped to these codes. The importance of high expectations - often described as a "push" - was viewed as an enabler of success. Students spoke of their teachers' encouragement to participate in STEM opportunities, with one commenting "if they believe we can do it, that in itself pushes us to want to do it" (S3, St1) and another referring to "a big push for women in engineering" (S3, St5). Two principals identified changes between the previous and current school "STEM culture." One noted when she started "students weren't being challenged in mathematics" (S3, P), while another mentioned the resistance of staff who were previously "left alone to do their own thing" (S4, P). However, teachers were generally pragmatic when setting and managing expectations, such as "starting off with expectations in the middle" (S4, T2) and ensuring they were transparently communicated to students and parents. All staff viewed STEM as a priority area, and a significant contributor to holistic student development.

Approaches to leadership of STEM reflected views about the importance of leadership stability, leadership style, trust, professional capital and student empowerment (29 refs). Teachers valued leaders who were approachable, forward thinking, and not afraid to push back against system-level directives. Principals were unanimous that "leadership density" was key to STEM initiative success, which one principal described as "leadership that is deep and solid, distributed across the school, that enables our young people… and has the support of our parent community" (S1, P). Staff in School 1 recognised that empowerment of their colleagues and students involved a balance between trust, forward planning, and leveraging individual and collective knowledge and skills. As one teacher commented, "I will be completely turned off if I don't get the opportunity to really tap into the things I really want to do as a teacher" (S1, T1).

Participants recognised the importance of partnerships for supporting STEM in their schools (26 refs). These included links to the tertiary sector and local council and industry, as well as participation in festivals and public events. Universities were frequently viewed as a source of STEM opportunities, mentors, and authentic learning experiences, often playing a key role in broadening students' understanding of STEM practices and careers:

We got to go to the [local university]… and they put lab coats on and they were scientists and they got to do some hands-on experiments. But the power for them to actually… just seeing what it's all about and talk to young scientists who were explaining to them about some of the things that they were doing at university… (S4, T1).

Partnerships were deemed important, as one principal described, for "making sure that we have impact and influence beyond our school" (S1, P). However, staff in School 3 acknowledged the difficulty of developing and maintaining industry partnerships. As one teacher explained, willing industry leaders often lacked more nuanced understandings of how schools operate, and how their businesses might best contribute to meeting students' learning needs. This sometimes manifested in tensions between school and business priorities (S3, T2).

Teachers and students unequivocally valued clear, visionary STEM leadership. Although the vision in each school took a different form, high expectations - variously referred to as *great heights*, *extraordinary learning*, *improving outcomes*, and *best practice*, was a uniting theme (11 refs). Evidence played a critical role in determining the attributes of STEM learning excellence, but both teachers and students strongly regarded 'shared ownership' of the vision for STEM as necessary for achieving such excellence. As one principal described, the school's collective vision was instrumental in the empowerment of students:

[Our] vision is *extraordinary learning driven by curiosity and challenge and inspiring confidence and passion*. So that drives our work… [and] is actually what we live and breathe. Our hope here is actually around providing opportunities for students to be curious and to work together to try and come up with their perspectives, their solutions, their ideas (S1, P).

All principals believed that teachers' professional capital and collective efficacy were integral to the success of STEM curriculum, while teachers and students valued their principal's vision for STEM, and the support they received to align this with classroom programmes and practices.

7.2. STEM pedagogy

Experiential learning was widely supported as an effective way to develop STEM knowledge, skills, and dispositions (109 refs). Students viewed STEM as immersive, fun, and involving experimentation, problem-solving, and teamwork, with some suggesting the authentic and "open ended" nature of experiences enhanced interest and motivation. Classroom observations supported the experiential nature of many STEM learning activities such as designing powered paper aircraft (S3) and improving gold mining tools (S2). In School 4, the principal commented on the school's farm as an ideal context for experience-based STEM learning:

So we're really embedding it [the farm] in the STEM work that they do. And this year it's become even more interactive, so the kids get up, they are over there, they touch the animals, they talk about why they're warm, why they're soft... listening to their heart, feeling their heartbeat… (S4, P).

Teachers in three schools viewed experiential approaches to STEM as an alternative to rigid, assessment-driven curriculum. One of these schools had implemented a weekly, 100-minute STEM challenge, where "we just play, we just have fun … there's no assessments, there's no curriculum, there's just us delivering what we think the kids can really benefit from" (S1, T1). Classroom observations identified numerous extracurricular activities such as robotics, Lego, coding, and Makerspaces for students to experience working with tools and materials in practical programming and making tasks (e.g., S3).

Despite teacher modelling being less represented in data (7 refs), the depth of detail indicated it was a valued approach for illustrating methods, dispositions and success criteria for STEM learning. In particular, teachers with industry backgrounds recognised the importance of being seen by their students as "model" STEM learners themselves. As another commented in relation to an industry-background colleague, "he's so passionate about what he does with the science and STEM… [and] it's been really powerful having and instilling that passion in the children" (S4, T1). Modelling also aligned with leadership of STEM and setting high expectations for staff. As one principal explained, "what you think you might be aiming for is not what you actually get, but it has taught me the importance at times of things like modelling and coaching and mentoring people" (S3, P).

Student-led Inquiry (35 refs) principally referred to research-based activities formed around 'investigable' questions or problems, which required students to use various information sources to develop and present defensible responses. This was evidenced in two schools via classroom observations where students explored advanced scientific principles without explicit instruction (S1, S3). To be effective, teachers in these schools considered STEM Inquiry tasks should focus on authentic problems of immediate relevance (e.g., S1 - designing a can-crushing machine to assist school rubbish recycling). Students favoured this approach, with some commenting on the motivating effect of this on work quality and output - e.g., (with reference to a peer) "one day (she) finished a whole page of research (on her STEM topic) - like, this big… full page of writing!" (S4, St8). Others considered Inquiry approaches directly aligned with learner competencies such as autonomy, problem solving, and research skills (S2, S4).

Collaborative partnerships (42 refs) were often based on student learning preferences, and adopted flexible pedagogies that encouraged teamwork, risk taking and innovation. Partnerships extended to colleagues, where teachers valued sharing STEM practices to build collective expertise and efficacy. Teachers commented in detail about how STEM initiatives represented a form of *reciprocal causality* - both emerging from, and further supporting, their STEM efficacy (109 refs). Celebrating successes was important to building STEM efficacy, and often involved sharing "not only *what they're doing* (students and teachers), but also the *outcomes of what they're doing*" (S1, P). Collective STEM efficacy was built on collaboration – as one teacher explained, "you get ideas from everyone… you still get the freedom to do what you want while also seeing what everyone else is doing" (S1, T1). Collaboration was particularly valued in interdisciplinary approaches where students were able to call on the knowledge of multiple teachers during STEM projects, supporting more individualised learning. As one commented, "teachers (are) always floating around, so it's not particularly hard to find a teacher who knows what you need to know" (S1, St4). Individualisation was supported by student-centred pedagogies that recognised student agency in decision-making. This extended to the selection and structuring of STEM learning units, through strategies such as "(getting) a group of students who want to contribute… their point of view about what they really want and what they like… and what is important" (S1, T1).

STEM pedagogies often reflected schools' socio-economically diverse and multicultural student populations (62 refs). Project-based pedagogies were seen to support equity, and principals were keen to use these to ensure *all* students had access to STEM opportunities considered valuable for their future lives. As one principal stated, "we ride every wave of refugee students that come… [and] you want to make sure that they get the opportunities that they deserve in terms of their (STEM) learning" (S3, P). Principals further understood the importance of teachers modelling dispositions they considered essential to STEM learning. As one stated, "it does the kids good to see that we're prepared to fail and [sometimes] can't do well, what they can do…" (S3, P). However, they also recognised the inadequacy of a single pedagogical method, identifying the need for "a multiplicity of styles to meet the particular situation - from direct instruction, through to inquiry-based, project-based, challenge-based, to mastery attention" (S3, P). Individualisation ensured STEM curriculum was relevant and beneficial for students who, due to cultural or socio-economic background, may not otherwise have considered STEM-related study or careers. There was strong commitment to equity and inclusion through pedagogy and curriculum that made STEM opportunities available to all, including staff without direct subject responsibility (44 refs).

7.3. STEM curriculum

Data indicates participants held variable understandings of, and motivations for, interdisciplinary STEM. Results for this category returned a high number of coded references (583) but low average words per reference (54.32), as participants tended to provide fewer details about interdisciplinary STEM in their school. Views and motivations for interdisciplinary STEM varied between schools. In two schools, specific advantages were identified for deepening discipline knowledge and supporting transfer across subjects: "the opportunities are there that we can really strengthen the transfer that students are able to make of their knowledge, their understanding, their skills - from one context to another" (S1, P). In others, interdisciplinarity served as a mechanism to co-plan and co-teach units, some of which had evolved into transdisciplinary units planned around authentic, problem-based tasks. As one teacher described, "we've come so far that the students don't actually know what subject they're being delivered" (S1, T1). Some tasks incorporated design thinking (16 refs), where students were introduced to the role of design through authentic, problem-based experiences: "you go through the whole cycle… you design something, you build something, you iterate it, you change it, then go back to the beginning" (S3, St4). Teachers in three schools associated design-based STEM with development of critical and creative thinking, problem solving, and risk taking. The iterative nature of design processes allowed students to "apply past knowledge to new situations" (S1, T1) and learn through reflecting on mistakes. In one school, design-based STEM extended to participation in community events including an "Innovation Expo," where a group designed, prototyped, trialled and presented, an ultrasonic sensor system to assist blind people's navigation (S1, St3).

While principals and teachers identified the importance of student engagement in authentic or 'real world' STEM (59 refs), the low average word count (41.49) indicated they provided limited detail or elaboration. Three principals mentioned the value of tapping into local businesses or community organisations, or using facilities owned by the school, as a means of adding authenticity to STEM learning. An illustration of this was one school's ownership of a farm, where students learnt about animal care and productivity, irrigation practices, factors affecting pasture growth, and automation opportunities and economics. The farm had "evolved from a very, very separate farm to a place that our students, as well as the visiting students, can engage in all elements (of STEM)" (S4, P). However, principals acknowledged difficulties sustaining external partnerships where commercial and educational priorities did not always align.

Other STEM curriculum challenges were noted by staff (92 refs), including students' "STEM readiness" and the need to "retrain" them in the different skills, dispositions, and competencies demanded by more independent, project-based curriculum. As one principal commented, "when I first came, we had kids who were good at the mindless drilling and skilling type thing, but not good at thinking" (S3, P). Another principal aligned this phenomenon with "the (dis)connection between a STEM strategy and the current improvement agenda" (S1, P), suggesting high stakes assessment, curriculum crowding, and teacher workload, worked against innovative interdisciplinary designs and students' STEM skill development. This awareness reflected in an explicit focus on transferable STEM skills, particularly in Schools 3 and 4.

In two schools, to develop interdisciplinary programmes principals provided release time for teachers to work in teams, where learning units were written and coordinated across disciplines (S1, S3). While in-the-classroom implementation was an individual responsibility, teachers in these schools noted this departure from traditional planning methods: "(this is) quite different from anything I've been involved in before, because… we're in interdisciplinary teams, and we plan as a group" (S1, T3). The blend of 'collaboration, autonomy and responsibility' linked to principals' leadership of STEM, where distributed approaches supported teachers' decision-making about the design of programmes that best met the needs of students. As one commented,

… teachers are actually given the license and the responsibility to make collective decisions about their timetable, their learning design, their assessment, the moderation of that assessment, the timing of those assessment tasks, the timing of the scope and sequence and the pacing of those learning designs (S1, P).

In all schools, extracurricular opportunities were important adjuncts to STEM curriculum (158 refs). These included clubs in robotics, engineering basics and electronics, in addition to participation in local and national STEM challenges and competitions. School 3 aligned some of these with interdisciplinary curriculum units at years 9 and 10, enabling students to link school-based with extracurricular STEM learning. Students appreciated "the freedom we (they) are given" (S3, St9) though this approach, which allowed them flexible access to equipment such as 3D printing, laser cutting and design studios to further their STEM projects.

7.4. STEM outcomes

Principals and teachers identified assessment of interdisciplinary STEM as challenging, and at-times oppositional to conventional assessment requirements that focus heavily of external examinations (75 refs). Although they saw potential for assessment of interdisciplinary STEM via rich, project-based tasks, teachers were realistic about their capacity to do this, with one commenting, "the best place is to put an assessment and bring in the content that we're required to deliver" (S1, T1). The tension between mandated assessment and interdisciplinary STEM was apparent in all schools and viewed as an ongoing concern: "the challenge we've got as educators is to keep the good and not to be become overly sensitive about results in NAPLAN (Australia's National Assessment Programme — Literacy and Numeracy) [since] they're just a measure at one point in time" (S3, P). Teachers nonetheless recognised the value of interdisciplinary STEM for engaging for all students, highlighting evidence beyond standardised assessment as examples of this (90 refs). These included higher numbers of students studying STEM subjects at university (S1, S3), improved academic achievement of students who struggled in other subjects (S2), and self-efficacy (S4). These outcomes were strongly linked to the engaging and authentic nature of learning in interdisciplinary STEM. As one teacher described, "they're investigating their own learning abilities, their own attitudes, dispositions, that growth mindset and understanding how the brain works …[and] it becomes really empowering to them" (S1, T1).

7.5. School culture and context

All schools showed commitment to establishing a STEM culture supportive of risk-taking and learning from failure (18 refs, av. 4.25 words/code). One principal described this as "failing forward" (S3, P), where students take risks and view failures as valuable learning opportunities. However, teachers described challenges working with risk-averse students, noting that some were inclined to "opt out" due to difficulties experienced transitioning to environments demanding more independence: "I caution them against that (leaving) because even though they find it very difficult … they just feel uncomfortable most of the time because they're learning" (S1, T2). Regardless, principals and teachers understood the importance of STEM knowledge and skills for their students' futures, recognising the value of practical, problem-based approaches for building valued 'soft skills' such as creativity, autonomy, critical thinking, teamwork, and problem solving (35 refs). As one principal commented, "the problem we face is [that] no one's quite sure of what the future and jobs are going to be" (S2, P). The suitability of project-based STEM as preparation for the future was also well understood by students, who appreciated the opportunities it presented to exercise their talents. As one explained, "I think I would like to do a job in STEM because [it's where] I'm using my imagination and my creativity" (S2, St1).

Professional learning in all schools supported staff capabilities by providing internal and external mentoring and training (59 refs, av. 83.81 words/code). Some of this occurred through attendance at courses and conferences, while other opportunities were accessed online using synchronous and asynchronous technologies (e.g., S3). All teachers and principals used technology to network with remote colleagues, further supporting the sharing of ideas and generation of new knowledge enhancing their STEM curriculum. In two schools professional learning mainly took the form of internal peer-learning and co-teaching through sharing of successful STEM experiences and knowledge, or working alongside colleagues in co-taught units (S1, S4). Peer-learning was particularly effective in School 4, where colleagues mentored new teachers to build knowledge embedding farm-based STEM experiences in their curriculum. As the principal commented, (our STEM leader) "takes teachers out onto the farm so that they become more aware of what it looks like out there and what they can do [STEM-wise]" (S4, P). Other schools leveraged external professional learning provided by state authorities, or accessed training through collaborative partnerships with nearby universities (S 2, S3).

Schools invested heavily in equipment and infrastructure to support STEM programmes (113 refs, av. 74.36 words/code), but also accessed free resources such as a local wildlife sanctuary, a museum visitors' centre, and a government research agency. Principal leadership was critical to resourcing STEM, and teachers acknowledged the freedom and support they were given to resource new initiatives. As one commented, (the principal's) "really good at saying, 'yes, this is something we need to build on, here's the money to do it, and we're going to support you in making the changes'" (S2, T3). Although parents represented an important resource, all schools struggled to engage them meaningfully with their interdisciplinary programmes (23 refs). Principals noted parents' preconceptions about integrated STEM curricula being less demanding and less effective than single discipline approaches: "the biggest challenge is our students and our families understanding the value of having a more interdisciplinary STEM curriculum, versus having a purer discipline-based grounding" (S1, P). Despite this, all principals saw this as "work in progress," and were keen to communicate to parents at every opportunity the positive outcomes from their interdisciplinary programmes, often using social media to demonstrate the breadth and depth of learning that occurred in them.

8. Summary and conclusion

Responding to question 2 and consistent with much literature (e.g., English, 2016; Falloon et al., 2020; Holmlund et al., 2018; Timms et al., 2018), these four schools pursued very different approaches to STEM. However, in each case the elements of the OECD model were valuable for understanding the interaction between, and overlapping nature of school culture, curriculum, pedagogy and leadership in the formation of practices and programmes, and revealed the challenges that some schools experienced - especially secondary schools, in attempting to transition to interdisciplinary STEM curriculum. Consistent with research (e.g., Fullan, 2003; Rose et al., 2019), leadership that created school cultures and climates supporting risk taking and innovation, was at the core of effective STEM education. The leadership capacity of principals to communicate a strong purpose and vision for STEM based on well-developed understandings of the current and likely future needs of students, was critical. Purpose was a consistent and unifying factor driving STEM, and was influential in decision-making relating to professional learning, resourcing (digital and non-digital), curriculum, and pedagogy supporting programmes. Interestingly, all schools adopted some form of distributed leadership of STEM, with teachers holding significant autonomy and often financial delegation to design programmes they saw as best meeting the needs of their students. However, principals were still central to establishing a "STEM culture" based on solid understandings of the importance of STEM knowledge, skills and dispositions (and modelling these themselves), high levels of relational trust, professional belief in the capabilities of teachers and students, providing autonomy with accountability, and support for risk taking and "failing forward." However, it was also clear, especially in the secondary schools, that enacting this vision was complex and challenging. The OECD model elements helped understand the significant tension schools experienced between external "high stakes" assessment (Content) and their transition to preferred interdisciplinary STEM (STEM curriculum). It also revealed the need for major organisational and system changes (Organisation), and specific professional learning in new pedagogies and assessment methods to allow teachers to plan, teach and assess project-based units in teams (Pedagogy, Resources). In these respects STEM presented a disruptive innovation, generally resulting in interdisciplinary approaches being limited to the junior school where constraints could be mitigated, or occasional units being designed around mandated content knowledge.

Notably, leadership of STEM in these schools involved much more than simply espousing a vision. While distributed leadership was common across schools, this did not mean principals delegated complete responsibility for STEM to teachers. In all cases, principals fully engaged with STEM programmes, often providing classroom assistance or helping coordinate external STEM events or competitions. Through this "hands on" approach, these principals set high expectations and modelled the type of behaviours and dispositions they expected from staff and students. Consistent with other recent studies (e.g., Rose et al., 2019), active principal engagement was fundamental to forming and enacting a clear purpose and vision for STEM. It also supported professional learning, resource and staffing decisions, through building better 'first hand' knowledge of the needs of teachers and the progress of students. Additionally, principal modelling served as a powerful motivator, creating confidence in teachers to try new approaches to curriculum and teaching that departed from conventional methods. Furthermore, principal modelling supported teachers' efforts to educate parents about the nature and value of learning using interdisciplinary approaches. As in other studies (e.g., Hutchinson, 2013), meaningfully engaging parents in STEM curriculum was an ongoing challenge, but recognised as one that needed to be addressed and could potentially yield substantial benefits. All principals actively communicated with parents to promote positive outcomes from STEM and build external partnerships and support for initiatives.

Finally, in this study rich data from multiple perspectives were innovatively analysed to better understand the most influential factors on schools' STEM trajectories. This was supported by classroom observations which indicated a high degree of fidelity and consistency with the interviews, providing confidence that details communicated were consistent with actual classroom experiences. However, these schools were not chosen because they displayed "exemplary" approaches to STEM. Indeed, literature indicates little is known about what exemplary practice actually is, or what and how outcomes from particularly interdisciplinary STEM can be recognised and evaluated. Instead, they were selected because they were identified as delivering STEM curricula that were deemed effective for meeting students' learning needs in their local context. While leadership was the unifying factor, each school programme was quite different in nature, suggesting what is effective STEM in one context may not apply to others. This highlights the need for further studies specifically connected to different contexts and environments, that will provide deeper insights into common factors that promote effective school STEM curriculum.

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Appendix

Appendix is available here.