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Investigating the role of self-selected STEM projects in fostering student autonomy and self-directed learning

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Abstract

Research in STEM education has focussed on integrated STEM projects that combine knowledge and skills across science, technology, engineering, and mathematics. These integrated STEM projects are typically designed by teachers or researchers addressing a limited range of topics that do not always cater well to the diversity of interest among children and adolescents. By contrast, self-selected projects where students have more choices and autonomy in selecting their own projects are relatively rare. Consequently, there is a gap in the literature on students' learning experiences when they choose and develop their own STEM projects. This study aims to examine the classroom experience and enactment of a high school STEM course designed for Grade 9 and 10 students (14 to 16 years old) to carry out a project of their choice aligned with the theme of sustainability. A case study methodology was used to investigate eight students' lived experiences in making connections to STEM. The study reveals the nature of students' self-directed learning experiences as they chose their own topics of exploration and subsequently developed their respective STEM-related projects. It also illuminates the alignments and tensions between STEM integration and various aspects of students' self-directed learning, including intrinsic motivation, open-ended tasks, goal setting, design thinking, collaboration with external partners, curriculum constraint, and time management. The implications of the study encompass student autonomy and agency, the significance of authentic problems and themes in STEM education, and the role of curriculum in facilitating self-selected projects.

Keywords Project-based learning · Self-directed learning · STEM integration · Student agency · Sustainability

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Introduction

STEM integration is frequently promoted as an interdisciplinary teaching approach that combines knowledge and skills across the four disciplines of science, technology, engineering, and mathematics (Moore et al., 2020). The rationale for STEM integration is often cited as a means to increase students' engagement with STEM subjects and selection of STEM-related careers, develop twenty-first century skills such as problem solving, critical thinking, collaboration and digital literacy needed in the workplace, and prepare a future citizenry in making informed decisions on contemporary issues, such as climate change, pandemic control, automation, and sustainable living (Millar, 2020; Tang & Williams, 2019). Consequently, there have been numerous studies reporting various integrated STEM projects in primary and secondary schools in recent years (e.g. Wieselmann et al., 2020).

One common issue encountered in the design and enactment of integrated STEM projects centres around students' choice and agency (Roehrig et al., 2021). Agency is defined as the capacity for strategic action and self-determination, transcending the traditional focus on individual motivation and instead emphasising the connection between individuals with their social and material environments (Rappa & Tang, 2017). McLure et al. (2022) reviewed the literature and found that many of the topics in integrated STEM projects were largely determined by the teachers or the researchers they worked with. For instance, it is common for students to be given an assigned project, such as designing a stable wood house in windy conditions (Barrett et al., 2014) or building a robotic arm for a competition (Chu et al., 2020). Aligned with the pedagogy of project-based learning, these teacher-chosen projects typically promote students' self-directed learning (Loyens et al., 2008; Mustafa et al., 2016). However, students are often not given a choice in deciding the problem or project itself, which would determine the topic of what they are learning. This lack of choice does not cater well to the diverse range of interests among children and adolescents. By contrast, we define *self-selected projects* as those where students choose their own individual projects and topics. We postulate that self-selected projects allow students to have more ownership, agency, and authority in directing their own learning as well as making personal connections to STEM. However, empirical studies of self-selected projects in STEM education are currently lacking.

To address the above-mentioned research gap, the purpose of this paper is to examine the classroom experience and enactment of a course designed for Grade 9 and 10 students to carry out a project of their choice aligned with the theme of sustainability. In particular, the students' individual selection of STEM projects provided an opportunity to investigate how their self-selection influences their self-directed learning and lived experiences in making connections to STEM. As such, we frame this study based on the literature of STEM integration, project-based pedagogy, and self-directed learning. The research question that guides this study is: What are the students' self-directed learning experiences that result from their self-selection of STEM projects?

Literature review and theoretical framing

Self-directed learning

According to Knowles's (1975) seminal work, self-directed learning (SDL) is defined as

> a process in which the individual takes the initiative, with or without the help of others, in diagnosing their learning needs, formulating learning goals, identifying human and material resources for learning, choosing and implementing appropriate learning strategies, and evaluating learning outcomes. (p.18)

This educational construct was originally conceived in adult education to represent a vision, where a mature learner sets their own goals, finds resources, and evaluates their learning (Garrison, 1997), both within formal (e.g. higher education, professional training) and informal contexts (e.g. lifelong learning). Given the appeal of SDL to active learning, this construct has been widely understood and applied in different contexts. This diverse application has somewhat led to SDL being seen as an umbrella term incorporating various educational processes like goal setting, self-regulation, and increased ownership (Loyens et al., 2008).

SDL has also been widely applied in the literature of Problem-based Learning (PBL; Ge & Chua, 2019; Loyens et al., 2008) and Project-based Learning (PjBL; Davidoff & Pieiro, 2017). Loyens et al. (2008) reviewed the literature and concluded that PBL can foster the development of SDL. Their review also brought up the degree of control and freedom given to the 'self' in SDL. They noted various studies offered varying degrees of choice in the learning process, ranging from choosing the learning task (highest freedom) to choosing the learning strategies, activities, and resources (lower freedom). Along this distinction, they clarified the difference between self-directed learning (SDL) and self-regulated learning (SRL). 'Both SDL and SRL involve active engagement and goal-directed behavior' but 'in SDL, the learning task is always defined by the learner. A self-directed learner should be able to define what needs to be learned' (Loyens et al., 2008, pp. 417–418). Based on this distinction, they argue that SDL is a broader concept that also encompasses SRL.

For our purpose, Loyens et al.'s (2008) distinction raises the need to consider a nested hierarchical level consisting of problem, task, and strategy in order to evaluate the level of freedom and choice given to students. Given an assigned problem in PBL (or an assigned project in PjBL), studies in SDL advocate that fewer guidelines should be given so that students can generate their own tasks and specific goals they need to learn and thus solve the given problem. Some examples of tasks include searching for articles to read, collecting data, and writing a report (e.g. Verkoeijen et al., 2006). Once a task is determined, the next level requires students to identify the strategies to regulate their learning activities or determine the resources they need to complete the task, as advocated in SRL research (see Panadero et al., 2018). Therefore, a given problem or project would incorporate numerous tasks, which would themselves incorporate numerous strategies, activities and resources, and so on.

Studies of SDL focus on student autonomy at the level of task, while studies of SRL focus on student autonomy at the lower level of strategy (Loyens et al., 2008). However, at the higher level above the task, the problem or project is usually predetermined by teachers, even in SDL studies. In Loyens et al.'s (2008) review and our own review, none of the studies in SDL provided the flexibility for students to choose their own topics, which will link to the choice of problems and projects in PBL and PjBL, respectively. Therefore, while SDL provides a high degree of freedom for students to determine their learning goals in terms of the task, it does not equate to giving students' choices over the specific topics or content area they want to learn. Studies that examine the learning experiences of students selecting their own projects are relatively rare.

STEM integration and project-based pedagogy

There is currently a lack of a consensus in the literature on the definition of STEM integration (Moore et al., 2020). Most researchers generally view STEM integration as a transdisciplinary pedagogy that emphasises the content and/or practices from different STEM disciplines (Nadelson & Seifert, 2017). Moore et al. (2020) identified four major themes emphasised in the literature of STEM integration. The first theme is that the instructional activities used in STEM integration should focus on *real-world problems*. Such activities generally require students to engage in an 'authentic' problem that parallels what STEM professionals (e.g. scientists, engineers) do in the contemporary workplace. The second theme is that STEM integration should emphasise the *shared ideas and skills* across the disciplines. These shared ideas and skills can include specialised vocabulary, representational systems, and 'big ideas' used in STEM (Nathan et al., 2013), as well as twenty-first century skills such as collaboration, creativity, communication, and system thinking (Stehle & Peters-Burton, 2019). The third theme revolves around the *degree of integration*. Many researchers use a continuum to describe the degree of STEM integration, ranging from multi-disciplinary to interdisciplinary and transdisciplinary (Nadelson & Seifert, 2017). In a transdisciplinary approach, the boundaries across the STEM disciplines blur as students undertake real-world problems and projects.

The last theme identified by Moore et al. (2020) revolves around the *pedagogical models* used to design and implement a series of lessons that are aligned with STEM integration. These models typically draw on theories from social constructivism and share many similar characteristics, including active and student-centred learning, meaningful learning experiences, and teachers as facilitators. The model that is most relevant to this study is project-based learning (PjBL). PjBL provides opportunities for students to 'construct knowledge by solving real problems through asking and refining questions, designing and conducting investigations, gathering, analyzing, and interpreting information and data, drawing conclusions, and reporting findings' (Blumenfeld et al., 2000, p. 150). According to a review by Mustafa et al. (2016), PjBL is the most common pedagogical model that is used by researchers to implement STEM integration.

Another common pedagogical model used to support STEM integration is the engineering design process (EDP), or sometimes called design-based learning. Unlike scientific inquiry that tends to involve investigable questions and evidence-based explanations, the 'goal of engineering design is to produce a workable model with no one correct method or procedure' (King & English, 2016, p. 2763). This engineering design goal typically involves a number of pedagogical characteristics, such as constructing a physical product or model, using engineering thinking to solve problems, as well as several iterative steps in the design cycle, such as empathise, define, ideate, prototype, and test (Hasso-Plattner Institute of Design at Stanford, n.d.).

Research gap

Within the STEM education literature, there is a lack of studies that apply a SDL framework to investigate students' learning experiences, and even fewer focussing on students' choices of their own topics and projects. In one study by Hew et al. (2016), teachers from 17 schools in Hong Kong took part in professional development workshops to understand the various aspects of SDL and then design lesson units that use an interactive and assessment platform to enhance student learning. Based on the schools' experiences, they developed a framework consisting of three enabling factors—personal attributes, autonomous processes, and learning context—that promote SDL in science education. Although the lessons that promoted SDL in Hew et al.'s (2016) study 'tended to utilise more open-ended inquiry tasks with real-life relevance' (p. 683), the lessons still followed prescribed content standards and objectives which limited students' choice of projects. In another study in the United States, Sahin (2015) developed and investigated a STEM teaching model that included a teacher-directed teaching and student project components. The student projects followed the principles of SDL and PjBL to promote student interest and voice in learning about STEM. However, the choices offered were also limited as the students could only choose from a list of projects that were aligned with the topics already taught by the teachers. Consequently, there is a need to examine students' self-selected STEM projects where they choose their individual topics of exploration.

Methodology

Research design

This paper utilised an instrumental case study (Stake, 2000) to examine the enactment of a STEM course designed for students in a secondary school to carry out self-selected projects. A case study is particularly useful for our purpose as it provides a detailed and holistic understanding of the participants' lived experiences in a bounded system, which in this case, is the STEM course as it occurred within the school curriculum. Given the highly contextual nature of a case study, our purpose is not to make universal claims regarding the design and implementation of integrated STEM. Instead, as the central phenomenon of interest is the connection between SDL and STEM education, the purpose of the study is to generate a contextual and thick description (Denzin, 2002) of students' self-directed learning experiences as they took part in the course designed with STEM integration in mind.

Research site and context

This study is situated in Queen's College—an independent school located in a large metropolitan city in Australia. The STEM course was designed as a non-compulsory elective for Year 9 and 10 students in Queen's College. As stated in the course program, the course was 'intended for students to develop their capabilities within the STEM disciplines to build and design innovative solutions guided by the UN 2030 Sustainable Development Goals'. In this course, students were to identify a problem in relation to one or more of the 17 Sustainable Development Goals (SDG) identified by the United Nations, and subsequently design and implement solutions to address the problem. In working towards those solutions, the course intended students to 'work collaboratively in teams, integrate knowledge from STEM and Humanities (e.g., geography, civics and citizenship), develop critical thinking and project management skills, and develop attitudes of empathy and social responsibilities'.

The course took 18 weeks over two academic terms to complete, with three lessons per week. Table 1 shows an outline of the course and how each week was aligned with key components of STEM integration, PjBL, and/or EDP. The course was designed by Ms. Fitzgerald who is an experienced teacher knowledgeable in STEM education and project-based pedagogy, both in Australia and in the United Kingdom. She has more than 15 years teaching across mathematics and science, with a passion for sustainability and integrating these elements into a project-based curriculum. Eight students (six boys and two girls) enrolled for the course as an elective. This study adhered to the ethical considerations and was approved by the Human Research Ethics Committee of Curtin University (Project number: HRE2021-0420). To safeguard the privacy and identity of all participants involved in this study, pseudonyms have been used to replace the school's and their names.

A unique feature of the STEM course was allowing students to choose their own topics of exploration within the scope of one or more of the SDGs. In addition, each student had to choose their own partner to identify and work on a common topic that resonated with both of them. Initially, there were four groups of two students. Three groups decided to work on the topics of bird conservation (Jason and Kenneth), microplastics (Marvin and Adam), and gender equality in STEM (Angeline and Christine). One group could not agree on a common topic and thus they decided to work separately, resulting in one student (Harry) focussing on river quality while the other student (Steve) focussed on bat conservation. The breakdown of the student groups, topics, goals, and targeted SDGs is shown in Table 2.

Another interesting feature of the course was the emphasis on working with external partners from the local community. With the help of Ms. Fitzgerald, the students were encouraged to identify and contact local professionals who had

Table 1 Course components and activities

Week	Key Focus	Main Activities & Ideas	Link to STEM, PjBL, & EDP
1–2	Understanding UN sustainable development goals	• Explore the 17 UN Goals and their related societal issues and perspectives • Identify individual goal of personal interest and importance • Establish small groups based on common goals and interests • Introduce ePortfolio and other assessment requirements	Investigate real-world global problems
3–4	Empathising with local community and identifying the problems/needs	Each group to: • Analyse issues and needs of local community • Make connection and plan working relationship with active local members of the community • Identify a problem/need as the focus of the project	Empathise & define local problem
5	Learning the engineering design process	• Introduce the Design Thinking Process from Stanford Institute of Design Each group to: • Work through the Design Process to the local issue related to the goal they identified	Design thinking
6	Pitching group ideas	Each group to: • Prototype a solution to their problem using the DT process • Pitch prototype to the class in a presentation and ask for feedback	Ideate prototype
7	Responding to feedback	Each group to: • Reflect on feedback received from their pitches • Modify and improve project plan	Improve prototype
8–10	Detailed planning of group projects	Each group to: • Create their vision, strategy, resources, planning documents, and timeline • Propose and contact external STEM professionals	Planning investigation collaboration

Table 1 (continued)

Week	Key Focus	Main Activities & Ideas	Link to STEM, PjBL, & EDP
Term break (2 weeks)			
11–15	Implementing group projects	Each group to: • Work on project implementation, documentation, and reflection • Collect data from fieldwork (for some groups) • Consult and work with external STEM professionals for information, resources, and feedback (for some groups) • Create and improve group artefact	Conducting investigation Creating artefacts Collaboration
School exam period (2 weeks)			
16	Communicating group projects	Each group to: • Present their projects and findings to peers and panel of educators and experts • Further revise/improve their artefacts and presentations	Report findings Communication
17–18	Showcasing group projects to school community	Each group to: • Present their projects and findings in various school events and learning festivals • Finalise ePortfolio for assessment	Report findings Communication

Table 2 Participants and topics of STEM projects

Group composition	Topic	Project Goal	SDGs	External Partners
Jason, Kenneth	Bird Conservation	To build bird boxes for Australian ringnecks in the area and promote the boxes to the public	Life on land	A freelance photographer and environmentalist
Marvin, Adam	Microplastics Pollution	To design and test a machine that can remove microplastics waste	Life below water	Engineers from a local outreach company
Angeline, Christine	Gender Equality in STEM	To conduct and evaluate a workshop for female students to raise STEM awareness and passion	Gender equality	Education researchers from a local university
Harry	River Quality	To investigate the quality of the water in Buffalo Creek	Clean water & sanitation	Local city council
Steve	Bat Conservation	To build bat boxes in the area to protect them from deforestation	Life on land, Good health, and well-being	Local city council

expertise in the students' topics. A number of external partners responded with useful resources and feedback to support the students' projects. This external support and collaboration will be further described in the findings.

Data sources and analysis

The data for this case study were generated through ethnographic methods comprising interviews, classroom observation, video recordings, field notes, and student artefacts. Three researchers took on the role of participant-observers and observed seven selected lessons (6 h and 45 min in total) in order to capture a range of teaching and learning activities from the course. These lessons included numerous student discussions, student presentations, workshops conducted by students and external partners, and a fieldtrip to the beach. All the lesson observations were video-recorded, except for the first lesson where we had not yet obtained the students' and their parents' informed consent. The lesson observations not only provided insights into the enactment of the course, but they also informed the interview questions that were subsequently asked at the end of the course. There were three focus group discussions (FGD) with three student groups and one interview with the teacher. The students involved in the FGDs were Jason, Marvin, Adam, Angeline, and Christine.

For the analysis, classroom video data were first imported into the software *VNote 3.1.1* for collation, episode segmentation, and memo writing. The video stream for every lesson was viewed and divided into distinct and meaningful segments called episodes. Following Erickson's (1992) interactional ethnography approach, the boundaries of an episode are determined by notable shifts in participants' interaction or nature of the task; for example, when the class moved from group discussion to group presentation, or when a group began to search the Internet for resources. Written memos and labels describing the event were generated and tagged to every episode. This tagging of memos and labels helped to facilitate the analysis among multiple researchers as well as purposeful selection of episodes for further interpretation along with the interview data. To enhance the robustness of the analysis, selected episodes were frequently cross-referenced with corresponding interview segments where similar themes or activities were discussed, allowing for a more comprehensive and integrated understanding of the students' experiences.

For the interview data, the transcripts were imported into the software *NVivo 12* for coding and analysis. We first applied Hew et al.'s (2016) theoretical framework on SDL to identify instances of personal attributes, autonomous processes, and learning context that enabled or constrained students' learning experiences. The SDL categories and sub-categories were used as provisional codes (e.g. intrinsic motivation, goal setting) to exhaustively plough through the interview data. At the same time, we also coded instances of STEM integration based on the themes identified in the literature, such as real-world problem, authenticity, problem solving, in design thinking (Moore et al., 2020). These instances were constantly compared with others within and across codes to find consistencies and differences among them. Such constant comparison sought to rise above the descriptive details of the data and make connection with the literature at a theoretical level (Fram, 2013). In parallel, the video data mentioned earlier were revisited to identify visual and interactional evidence that supported or contrasted with the emerging themes from the interviews. This iterative back-and-forth between the two data sources enabled us to triangulate findings and strengthen the validity of our interpretations. At this stage of connecting to the literature, the memos and labels from the video analyses were interpreted in conjunction with the interview data analysis. Through this iterative process between theory and data, recurring themes and assertions were then generated and tested with confirming and disconfirming evidence.

This study follows a constructivist research paradigm (Guba & Lincoln, 1994). As such, the criteria used to establish the validity of this study are active engagement with participants, joint interpretation, and triangulation (Creswell & Miller, 2000). First, the role of the researchers as active participant-observers facilitated the building of trust and rapport such that the students were comfortable in revealing reliable information through observations and interviews. During the analysis, the researchers checked on one another's interpretations in order to establish some common understanding and joint consensus. Any disagreement and ambiguity in one another's claims and interpretations were discussed collectively. Lastly, the trustworthiness of the study was also strengthened through triangulation with the interview and video data. These data sources were used to support our search for confirming and disconfirming evidence during the analysis.

Findings

In this section, we report on the nature of students' SDL experiences as they chose their own topics of exploration and developed their respective STEM-related projects. In particular, the connections across various components of SDL and STEM integration are reported in three thematic areas: (a) motivated problem and authentic task in STEM, (b) goal setting and design thinking, and (c) collaboration with STEM professionals. We also focus on the alignments and tensions between STEM integration and a myriad of factors in these areas, such as intrinsic motivation, open-ended task, goal setting, design thinking, collaboration with external partners, curriculum constraint, and time management.

Motivated problem and authentic task in STEM

One of the most significant contributing factors to SDL revolved around the students' motivation that was shaped by their personal choices of the open-ended STEM projects. In particular, there are two key observations that emerged from the students' self-selected projects.

First, the students' motivation was built around their desire to do something about a STEM-related problem they identified in their local community. For instance, when asked about the key criterion for choosing their project during the interview, Marvin reported, 'you have to do something that would be possible to contribute to locally'. As both Marvin and Adam felt that microplastics pollution was an immediate and escalating problem in Perth, Australia, it was important for them to choose a project to which they could actively contribute instead of ideas they felt they had little agency in changing. They gave the example of climate change as a project that was difficult to find meaningful actions they could take.

The choice of doing something about a local problem was also echoed in Jason's project to build nest boxes for endangered birds in Perth. Similar to Marvin and Adam, he felt motivated to make an impact to his community. He was prompted by the project, to learn more on this topic in the future and consider working in the biodiversity and sustainability space. He talked about his goal and rationale in choosing their project:

> Actually making a difference believe it or not, in our local area at the moment. It's actually changing something… So I think just educating myself on what's actually happening in the world, and how to make small differences that make big differences.

Angeline and Christine also had the same desire even though their project was somewhat different. When the two girls learned about the unequal gender distribution in the enrolment of certain STEM subjects in high school, they felt compelled to focus on this issue. However, instead of examining gender equality which they recognised as a broad issue, they decided to tackle a 'much more local issue, which is the skew between males and females in STEM ATAR[1] subjects'. This motivated their project to organise and deliver a workshop to encourage Year 7 female students in their school to develop a passion for STEM. Angeline and Christine spoke about what they wanted to achieve from this workshop:

> We wanted to make an impact on current female students [in Queen's College], encouraging them to take up more STEM subjects. We wanted to make them aware of the different opportunities that studying STEM provide and the different aspects of STEM. We aimed to make, regardless of how small, an impact on future students.

Second, the distinction between an actual STEM project and a hypothetical 'school-based project' had an impact on the students' motivation. In this study, the nature of the project had been variously described by the students and Ms. Fitzgerald as 'authentic', 'real-world', 'open-ended', 'functional', 'hands-on', and 'actually doing something'. The students also frequently compared this experience with other school-based tasks. Adam and Marvin compared their project where they were given more choices and autonomy compared to 'projects' from other courses. They elaborated that the tasks from most school-based projects were hypothetical and set by the teachers:

[1] Australian Tertiary Admission Rank (ATAR) is a percentile ranking given to every student for a subject taken in Year 11 and 12 for admission to Australian universities.

> Adam: A lot of other projects, just like give set sort of tasks. Like, this one, you sort of come up with the task yourself.
> Marvin: And it's sort of like, unlimited scope, like most of the stuff that you do in school, it's just kind of like a hypothetical… this is an actual situation.

Similarly, Jason recounted the typical task in other courses tended to revolve around information acquisition and standardised testing, as compared to doing something functional. Compared to the prescribed tasks from most projects in which they had participated, the freedom to choose their own projects allowed he and his partner (Kenneth) to 'actually make and do something that is functional and helpful in a way'. As noted by Moore et al. (2020), this personal authenticity in an open-ended project is important in making STEM more culturally relevant and motivating for the students.

The nature of students' self-selected projects generally align well with the central theme of focussing on real-world problems in STEM integration (Moore et al., 2020). This alignment occurred in this case study even through STEM was not deliberately imposed as a criterion in restricting the nature of the project that the students must carry out during the course. While the term 'STEM' appeared in the course title and was frequently mentioned in class, there was no requirement, as expressed by Ms. Fitzgerald or the course documents, that the students must select a project that would be counted as 'STEM'. The only requirement that the students had to select was the SDGs identified by the UN (see Table 2). Within this broad parameter around sustainability, it appeared that most of the SDGs selected by the students were naturally connected to problems that are STEM-related, such as wildlife conservation and water pollution. This alignment between students' choices and real-world STEM problems was an important source that drove the students' SDL.

However, there was also tension in allowing students' self-selected projects. A good example is illustrated in the project by Angeline and Christine who focussed on the SDG of gender equality and chose a project focussing on STEM education for high school female students. The nature of their project in terms of the content area is closer to a social science topic than STEM. Ms. Fitzgerald was cognisant of this apparent tension between students' choices and connection to STEM, that is, allowing student flexibility had the risk of deviating from the focus of STEM. However, she was adamant that authenticity within the theme of sustainability was more important in driving the students' projects than, in her words, a 'fidelity to STEM'. This was also aligned with her pedagogical view in project-based learning (Krajcik & Shin, 2014), which she felt should be driven by authentic question and collaboration, instead of a set narrow topic.

According to Moore et al., (2020), the emphasis of STEM integration is not the specific content area but rather the shared ideas and skills across the disciplines. This aspect of STEM integration was echoed in Ms. Fitzgerald during the interview. Although she felt that the connection to STEM in some of the projects was often not explicit during the course, she could see the students' projects were related to STEM skills in many ways. She gave the examples of: 'asking big questions, developing an understanding of the knowledge base around them, finding the holes in that, and ideating around how they might change, and then obviously, the testing and the data collection'. Many of these STEM skills were also built into the engineering design thinking process that framed the students' projects. In summing up her views, Ms. Fitzgerald articulated that over the years of running this course, she had moved away from seeing STEM as a 'standalone' concept or subject area, towards a transdisciplinary process that is applicable in many real-world projects and industries, including business and humanities.

Goal setting and design thinking

Another crucial factor driving the students' SDL was goal setting. In this aspect, it is important to distinguish different levels of goal setting. As discussed in the literature review, many studies in SDL focus on goal setting at the level of task, while studies in SRL focus on goal setting at the level of strategy (Loyens et al., 2008). In this study, the students set their goals at the level of project which is broader than task and strategy (see Table 2 earlier). Once each group decided on a project goal, they then planned several goals at the level of task (e.g. build prototype, collect data), followed by more specific goals at the level of strategy (e.g. activities, resources).

A novel finding from this study is the negotiation between the teacher and the students in goal setting at several levels from curriculum to theme, project (topic), task, and strategy. At the broadest level of curriculum goals, Ms. Fitzgerald often spoke to the students about the course goals she set in order to meet the course accreditation requirements as well as the school's academic expectations, such as collecting evidence, compiling an eportfolio, and giving an oral presentation. At the next level, she also determined the theme of sustainability and the SDGs as the general parameters to guide the students' projects. As the SDGs cover a wide area, they did not restrict the range of topics explored by the students. It was clear to the students that these goals at the levels of curriculum and theme were non-negotiable. However, within this broad goal framework, there was sufficient flexibility built into the course that allowed students' autonomy in setting their goals for their individual projects, and subsequently the goals for the multiple tasks and strategies.

Allowing students to choose their own projects had significance in them setting their specific project goals and planning their tasks at different stages of the projects. For instance, Jason's group demonstrated these multiple goal setting and self-planning processes as they went through different tasks and stages of designing and building a functional bird box. After Jason talked about the importance of 'making a difference' to sustaining the biodiversity of his community, the interviewer followed up by asking him to describe the process the team went through during the project. Jason replied:

> Just want to find out what is our goal? What are we trying to do? And biodiversity, built in bird boxes, put them up. How do we make them so they're functional? What place do we put them up so that they work the best? So there's a bit of research, as previously mentioned those. Peter [A local environmentalist], he had a few documents that we saw, and then we built into our project of, so we could make it as functional as possible. And then yeah, pretty much just made some prototypes.

As seen from this excerpt, Jason talked about the different goal setting stages even though the interviewer did not ask about his goals. He highlighted a series of metacognitive (self-regulated) questions that Jason and Kenneth asked themselves, followed by an answer to their own questions. For instance, at the beginning, Jason reflected that they had been asking themselves what their goal was in terms of what they wanted to do at the level of task, and then figuring out that they needed to build bird boxes and install them in several trees within their school campus and nearby parks. Within this larger goal, he also mentioned other more specific goals at the level of strategies, activities, and resources, such as making the boxes functional, finding out the ideal locations, getting help from Peter (who was their external partner), and sourcing materials. Thus, the autonomy to set their own goals at multiple levels of project, task, and strategy was a key feature of the students' SDL in this study, as exhibited in Jason's group and also witnessed in other groups.

Allowing student autonomy in setting their own goals at the level of project, task, and strategy would require a mechanism that could enable students to reflect on their plans and make revisions when necessary. Ms. Fitzgerald was aware of this need in the design of the course. To facilitate this revision process, she introduced to the students the Stanford Engineering Design Thinking (empathise, define, ideate, prototype, test) during week 5 of the curriculum (see Table 1). In addition, during weeks 3 and 4, Ms. Fitzgerald facilitated a number of activities to develop students' empathy as they identified a need from the local community. Subsequently, two groups reported they used the design thinking process to some extent in order to guide their initial thinking and planning.

In terms of students implementing the engineering design thinking process, there was some variation in how different groups applied it. For Marvin and Adam's project, they did a lot of research during the define and ideate stages. They came out with a number of designs, some of which they later recognised during the interview were 'bad ideas'. Unfortunately, due to issues with their time management, they did not proceed to making a prototype to test, and possibly revise, those ideas. For Jason and Kenneth, while they felt the design thinking was useful, they skipped the define and ideate stages and proceeded straight to prototyping and testing. Part of the reason was because they already had the plans provided by the environmentalist Peter, so they just concentrated their efforts on building, testing and tweaking the prototypes. Nevertheless, they made some revisions to their design after observing the problems experienced by the Australian ringnecks with their boxes. Figure 1 shows a prototype made by Jason and Kenneth.

In theory, the design thinking process aligns well with the goal setting requirements in SDL as well as the open-ended nature of integrated STEM projects. However, in practice, there were several issues and tensions in how the students utilised design thinking. During the interview, Ms. Fitzgerald noted various extent of how students engaged with the revision process using the engineering design thinking. She recognised that 'the nature of their projects determined how well they engaged with it'. Thus, some groups made more revisions to their ideas than others. For instance, for students like Jason and Kenneth, engagement in the revision process was particularly evident as they actively embraced the value of revision and were open to altering their prototypes. Ms. Fitzgerald observed that these students

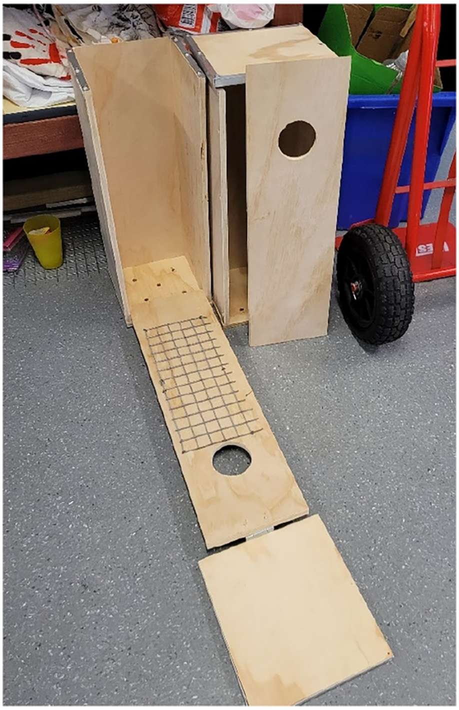

Fig. 1 Prototype of bird boxes for Australian ringnecks

showed a deeper understanding of the iterative nature of design thinking. However, she also acknowledged that this level of engagement was not uniform across all groups. While some groups demonstrated similar levels of active engagement and willingness to revise their work, others such as Angeline and Christine were less inclined to deviate from their initial ideas or engage deeply with the design thinking process. Ms. Fitzgerald remarked that varying levels of engagement could be attributed to the individual nature of the projects and the students' personal connection to their chosen topics. This variation in engagement, she noted, is a common occurrence in project-based learning settings and reflects the diverse ways in which students approach problem-solving and revision processes.

Collaboration with STEM professionals

Besides authentic problem and goal setting, another key factor that shaped the students' SDL and STEM learning was their collaboration with external partners. Some researchers have argued that STEM learning is not restricted to content mastery and classroom activity but should involve the community by inviting STEM professionals into the classroom (Myers, 2015). In this study, the involvement goes beyond asking STEM professionals to give a talk or bringing students for an excursion to their workplace. Instead, the students were asked to involve relevant experts in their projects and to actively work with them as external partners. The support from these

Fig. 2 Students separating microplastics waste from sand at a local beach

STEM professional experts received by some students made a significant impact to their learning experiences as well as the progress and quality of their work.

In the first place, many external partners provided useful documents and feedback for the students. For instance, Jason and Kenneth worked closely with Peter, a local environmentalist who builds nest boxes for birds in Western Australia. They received a number of designs from Peter and adapted them to develop prototypes for Australian ringnecks nesting in their local area. Angeline and Christine received support and advice from three researchers in a local university working in STEM education. One of the researchers further provided a validated questionnaire that the students later adapted for their workshop. In Marvin and Adam's project, two engineers from a local firm came to give a talk about microplastics to the class. They also provided some documents and advice to Marvin and Adam on possible designs to separate microplastics. One of the engineers later came to facilitate a fieldtrip to remove microplastics waste at a nearby beach. The engineer brought a machine designed by him to sift microplastic from sand (see Fig. 2), so that the students could test the machine and collect some data for their analysis.

The contribution of external partners was not limited to supplying information and resources that were beyond the teacher's expertise to the students. The collaboration with engineers, scientists, environmentalists, and university researchers was itself a valuable STEM learning experience for the students. According to Ms. Fitzgerald, engaging with actual partners outside the school was part of the objective in the design of her STEM course. She further elaborated:

> The objective is for the students to have the opportunity to engage with those real-world problems, work with partners outside of the school environment, using the resources they have available. So those partnerships could be with universities, with local industry, and with local business people.

Although the collaboration with STEM professionals brought a lot of benefits and opportunities, it also introduced a number of tensions. One major challenge was the coordination with external partners outside the school in terms of scheduling and alignment. Some groups struggled during their planning stage because they could not proceed with their plan until they talked to the relevant external partners. This issue was corroborated by Ms. Fitzgerald who reported several unsuccessful attempts when the students initiated contact with external partners. She gave the examples of Angeline and Christine being ignored in their initial contact as well as other partners who replied to the students but could not sustain the partnership. Despite these challenges, the students' experience with STEM professionals aligns with real-world collaboration in the workplace. This experience differed greatly from the typical school-based tasks where information is readily provided by a hypothetical and imaginary expert that was designed in the curricular task. The experience also pushed the students to develop their communication skills as they had to initiate contact and correspond with actual experts.

Related to the collaboration with external partners is also the challenge of time management, which is an important skill in SDL (Hew et al., 2016). The groups that had to wait for external partners to respond ended up with delays and not a lot of time for carrying out the rest of their projects. This problem with time management arose even though the students were introduced to several time management strategies, such as a Gantt chart, at the beginning of the course. The students were given ample time to plan their timeline during class. However, it appears that many students would still need to develop self-monitoring to adjust and manage their time in response to uncertain developments, such as delay from external partners.

This issue of time management with external partners needs to be considered within the context of a formal curriculum with regular class time. As the students needed to complete the projects within the semester, there was no opportunity to extend the deadline for their projects. The formal curriculum imposed a tension in the duration of the project. At the same time, it also provided key enablers to support the students' projects in terms of the course structure and multiple class activities. These support structures included formal learning of some project management skills (e.g. Gantt chart, design thinking) as well as the assistance from Ms. Fitzgerald in facilitating the contact between the students and the external partners.

Discussion

A central theme that resonated in the study is the role of student autonomy and choice in selecting their own STEM projects. Letting students select their topics gave them more agency to set their own goals, solve meaningful problems, and make a difference to their local community. This kind of autonomy is in line with the OECD's (2019) vision of student agency, as 'rooted in the principle that students have the ability and the will to positively influence their own lives and the world around them' (p. 2). In STEM education research, more work is needed to incorporate student agency by allowing students more flexibility to choose the kind of projects they want to investigate (McLure et al., 2022).

The novelty of this study centres on the recognition of student autonomy at multiple levels of 'self' directness and addressing the research gap at the level of self-selected project. Based on our findings in relation to the literature, we propose the following hierarchical model to help us distinguish and discuss various nested levels of autonomy and choice given to the students to direct their own learning (see Fig. 3). Most research in SDL and SRL have focussed on student autonomy at the level of task and strategy, respectively, with a predetermined project or topic

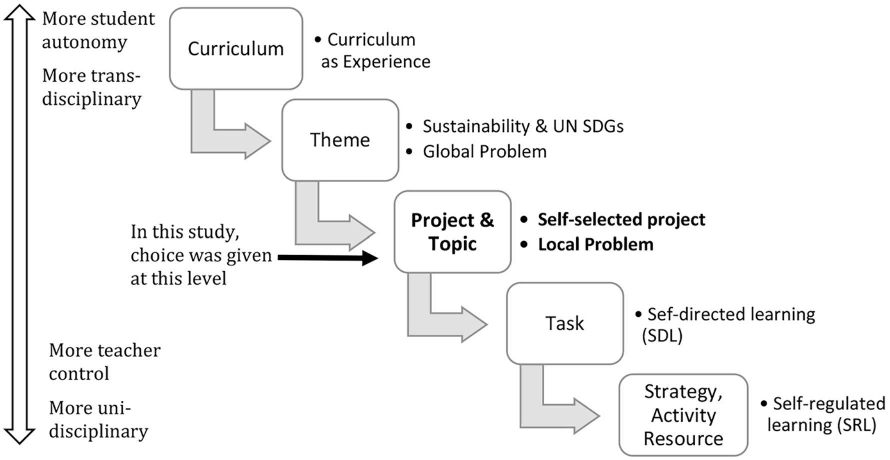

Fig. 3 Different levels of student autonomy

already given to them. In comparison, this study emphasises self-selected projects at a broader level whereby students chose their own projects and topics of exploration. Determining the overarching goal at the level of project would involve setting goals for specific tasks at the next level, which would in turn involve specific strategies, activities, and resources. In this sense, we argue that self-selected projects would naturally incorporate self-directed learning (SDL) and self-regulated learning (SRL) as well.

To align students' choices with the goals of STEM integration, Fig. 3 provides a useful way to discuss the level at which students should be given autonomy and the level that should be set by the course or teacher. In this study, while students were given the freedom to choose their projects, all the projects had to fall within the theme of sustainability and SDGs which was determined by the teacher. This negotiation between the 'global problem' set by SDG and the students' 'local problems' worked particularly well, as it provided an overarching theme towards a social or environmental problem despite the range of individual projects and efforts. Furthermore, the students could contribute to a larger common cause (i.e. SDG) by 'making a difference' to their local area in their own ways.

This study suggests that as we allow more autonomy at a broader level (e.g. project instead of task), the degree of STEM integration becomes more inter- and transdisciplinary as the boundaries across the subject areas become blurred. On the other hand, with student autonomy at a more specific level (e.g. task or activity), teachers retain control over the topic and subject area, which would make the integration more multidisciplinary or even uni-disciplinary. In the case study, given the theme of sustainability acting as the global problem, most of the projects identified by the students required the application of interdisciplinary STEM knowledge and skills to develop a solution to a unique local problem. In this regard, there were several interdisciplinary ideas and skills taken up and applied by the students despite the variety of self-selected projects, such as test, prototype, variable, and model. Lastly, sustainability was also a central transdisciplinary idea that integrates the STEM disciplines. We argue that the students learned about sustainability more meaningfully through self-selected projects than if they had learned it through a uni-disciplinary approach.

This study also contributes to the conceptual clarification of the term ‘project’ within the context of PjBL. There is often a tendency to conflate projects with tasks, wherein any form of self-directed task that provides autonomy for students to work independently, such as conduct investigation or internet research, is regarded as a ‘project’. However, the hierarchical model of student autonomy developed from this study (Fig. 3) sheds light on the distinction between projects and tasks. It demonstrates that a project encompasses multiple interrelated tasks nested within an overarching topic, and importantly, the choice of the topic should ideally be determined by the students themselves. When students are granted autonomy at the project level, including the selection of the topic, they naturally take ownership of the planning, implementation, and reflection processes involved in most of the subordinate tasks (Grainger et al., 2019).

Finally, above the level of theme, the broadest level in Fig. 3 is curriculum. The notion of curriculum can mean different things to different people (Connelly & Clandinin, 1988). For many people, curriculum can mean a subject matter with a fixed syllabus to deliver or a program of planned activities with predetermined learning outcomes (Schubert, 1985). In this study, we adopt Dewey’s view of curriculum as the process of enriching students’ experience and personal growth in a meaningful area (Schutz, 2017). While our view of curriculum in this study is evidently more open-ended and flexible, it is still a formal curriculum with regular classroom time, organised activities, and other instructional structures planned and mediated by a teacher (see Table 1); as opposed to an informal or non-formal curriculum that occurs as after-school or extra-curricular activities. The formal curriculum also includes several course accreditation requirements and summative assessments (satisfactory or unsatisfactory) in the form of student eportfolio and oral presentation. In this regard, this study sheds some insights on the implementation of self-selected projects within this curriculum structure.

Based on the findings from this study, future research could explore how varying levels of student autonomy in project selection could impact learning outcomes across different educational contexts. In particular, studies could further investigate whether a broader level of autonomy could have a bigger impact on students’ critical thinking, problem-solving skills, and ability to apply knowledge in real-world contexts. Additionally, longitudinal studies examining the long-term effects of student-chosen projects on their engagement and achievement in STEM subjects would be valuable. Research could also delve into the role of teacher facilitation in supporting autonomy at this broader level, exploring how educators can balance guidance with independence.

Limitations and implications

One of the major limitations in this study is the small number of students enrolled in the course. Thus, the findings may not cover a sufficient range of student experiences. In addition, the descriptions of the students’ experiences in this paper are specific to the context of this study and are not generalisable in the same way to other classroom situations. As a case study, our purpose is not to make a generalised claim that all students can and should do self-directed STEM projects, but to present a 'telling case' of what a particular enactment of STEM projects that allows student choice and agency would look like. As Stake (2000) argues, telling cases are interesting, not because they are typical or generalisable, but 'because it is believed that understanding them will lead to better understanding, perhaps better theorizing, about a still larger collection of cases' (p. 437). In this study, the cases concerned are the students' SDL experiences of self-selected STEM projects, which are rarely reported in the literature.

Furthermore, it is important to recognise that the study was conducted in an independent school in a major city, with a student body that may not be representative of the broader student population. This context included access to an outstanding teacher and strong connections with willing collaborators in the community, which likely contributed to the success of the self-directed STEM projects. Such resources and support systems may not be readily available in all educational settings, particularly in under-resourced schools or those with different demographic compositions. Therefore, the applicability of our findings may be limited by these factors. Future research should aim to replicate this study in a variety of educational contexts, including public schools and schools and under-resourced environments, to better understand the broader applicability and potential challenges of implementing self-directed STEM projects in diverse settings. This would provide a more comprehensive view of how student choice and autonomy in STEM projects can be supported across different educational landscapes.

The findings of this study shed light on the importance of incorporating self-selection opportunities in STEM education, particularly in the context of integrated STEM projects. Science or STEM teachers can leverage the power of self-directed learning and student agency by providing opportunities for students to choose their own individual projects and topics. By allowing students' ownership and authority in directing their own learning, teachers can tap into the diverse range of interests among children and adolescents (Grainger et al., 2019). Following this case study, teachers can consider the following steps and ideas in the implementation:

1. Implement a project selection phase: Select suitable themes from the STEM curriculum that allow student autonomy in exploring different project ideas and selecting topics aligned with their interests and passions. Open-ended themes linked to global problems, like sustainability, provide excellent options as they encompass diversity and relevance to real-world context, in addition to covering various aspects of science, technology, engineering, and mathematics.
2. Provide guidance and support: Once students have identified their topic of interest in the project, the next step is to guide the students through the required tasks, and subsequently for each task, the strategies, activities, and resources to achieve it. Figure 3, which shows the nested levels of *project*, *task*, and *strategy*, can provide a common vocabulary for teachers and students to communicate to one another as they work on the integrated STEM projects.

3. Foster collaboration and resource sharing: Create a classroom environment where students can communicate and share their chosen projects, allowing for peer feedback, collaboration, reflection, and refinement of their projects. Provide assistance and encourage students to connect with external STEM professionals to support their projects.

We are not advocating that all STEM projects must allow students to choose their own topics and projects they want to pursue. We recognise that many educators are working within the constraint of a more restricted curriculum with specific content standards as well as other challenges (e.g. standardisation, curriculum time, school culture). In this regard, the model shown in Fig. 3 does not prescribe others to adopt the view of 'curriculum as experience' as we have done in this study. Rather, our purpose of this study is to add a critical voice to the research conversation not to undervalue the role of student autonomy in their self-selection of STEM projects and the kind of learning experiences they will gain. We will need more research and case studies to show a greater range of student experiences under different levels of autonomy in different social contexts (as differentiated in Fig. 3). This will help us find an appropriate balance between curriculum standardisation and student autonomy/SDL in the design and enactment of STEM integration.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The research project adhered to the ethical considerations and was approved by the Human Research Ethics Committee of Curtin University (HRE2021-0420). All human participants provided informed consent to be interviewed and video recorded during the research.

Consent to participate The study presented in this article utilised datasets that are restricted due to privacy protection of the participants. Interested readers can request access to part of the datasets by emailing the corresponding author.

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