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A Cocurricular Framework for a Multinational, Vertically Integrated Engineering Design Project

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A co-curricular framework for a multinational, vertically integrated engineering design project

Abstract

In South Africa there is a need to address the lack of social and contextual relevance of existing engineering curricula. Education of the next generation of graduates has the potential to greatly impact society if their technical expertise are combined with personal and professional attributes to make them more socially-engaged and effective as leaders. Leveraging a project-organised curriculum as opposed to a more traditional approach has proven to be successful in cultivating these personal and professional attributes alongside technical development. But transforming a curriculum is a slow and arduous process. The curricula in the School of Engineering at the University of Pretoria are based on the CDIO framework, but limited resources and large student cohorts make it difficult to fully leverage the benefits of project-based learning within the formal curriculum. Resultantly, educators experiment with co-curricular initiatives to complement the personal and professional development of engineering students. The AREND[1] project is one such initiative. Since 2014, the AREND project has been an interdisciplinary, multinational, vertically integrated engineering design project founded exclusively on an experiential learning approach philosophy. It has been successful in cultivating innovative attitudes, professional skills, and early cross-subject synthesis in participating students. The co-curricular nature of the project has evolved over six years through trial and error and now fosters robust articulation with project-based and work-integrated learning modules in the formal curriculum. Strong articulation enhances the longevity of the project and the persistence and motivation of participating students. In this paper, we use a reflexive lens to explore the evolutionary stages of the AREND project since 2014. We connect the project leader's lived experience throughout this evolution to the theoretical underpinnings of co-curricular initiatives in higher education. Reflecting on the lessons learned during each stage, we provide an implementation framework for similar projects and offer long-term recurriculation guidelines for large cohorts.

Keywords: Project/Problem based learning, Vertically Integrated Projects, Co-curricular, Professional skills, Experiential learning

1. Introduction

The Engineering School at University of Pretoria follows the Conceive, Design, Implement and Operate (CDIO) teaching framework which stresses the importance of training engineers fundamental principles in the context of real-world systems and products. In some of the modules the CDIO teaching framework becomes a lens through which to facilitate problem/project based learning (PBL) activities to achieve specific outcomes. Teaching large student cohorts based on a PBL framework can easily become ineffective if there is a lack of curriculum overview and insufficient scaffolding of PBL skills for students [1]. Kamp [2] also stresses the urgency of developing curricula that emphasises

[1] AREND - Aircraft for Environmental and Rhino Defence

training communicative and innovative engineers for diverse workspaces as we move into transformation and globalisation in the 4th industrial revolution.

Full re-curriculation is challenging and has multiple risks, not even considering the lack of staff and time to do so, which means alternative solutions are explored. The AREND project is one such alternative, currently with 24 students. It is a multidisciplinary, multinational, vertically integrated engineering design project with a co-curricular framework integrated into PBL modules in an engineering school.

In a previous paper [3], we discussed the development of innovativeness as an engineering competency achieved through the AREND project. This paper explores the evolving framework of the co-curricular integration and categories of student involvement with some initial observations of cross-subject synthesis and development of professional skills as a result. The paper also considers future possibilities of the project, where the initial developmental phases were to ensure sustainability, we reflect on scalability of the AREND and similar projects to large cohorts.

2. Theoretical framework

2.1. A blended project and problem-based learning approach

Various authors have studied the differences between project and problem-based learning (PBL) [4]-[6]. Project-based learning typically is a more real-world directed application of knowledge while problem-based work takes a shorter time and is more directed to acquiring knowledge. The students' ability to be self-directed plays an important role in project-based learning in engineering since it requires technical (design, math, physics, etc), personal (time and resource management) and interpersonal skills (communication and teamwork) skills. Savage et al. [7] mentioned that self-directed PBL learning (the responsibility on the individual to initiate and direct the learning process) not only allows the student to develop their adaptability but also helps them develop an appreciation for the interconnected nature of complex multidisciplinary problems.

A wide variety of positive attributes have been linked to the use of PBL. Most notably is related to improved conceptual understanding and ability to apply knowledge, reasoning skills, teamwork and students' self-efficacy [8]-[12]. Some studies on student perception also report that their communication, decision-making, synthesis of information, autonomy and self confidence in competencies in their engineering degree were improved [13]-[17].

PBL has its own challenges and shortcomings. Heitmann [18] distinguishes between the product and content orientation of project work and the process and skill orientation. The former is concerned with "what was learnt" and "what was produced", while the latter is concerned with the development of the student's competence. The tension between these two orientations is ever-present. Client requirements, learning programme outcomes, financial and time limitations emphasise the product and content orientation. Meanwhile, the true value of project work as a learning approach is in the process and skill orientation. Mills and Treagust [5] suggest that one of the main challenges of PBL in engineering education is to ensure students still develop a strong fundamental understanding of engineering principles in addition to demonstrating higher levels of motivation and better communication and teamwork skills.

Ideally PBL experiences must be integrated throughout the undergraduate program, rather than a single capstone project, in order for learning to be most effective [19],[7]. Furthermore, if these projects are providing an integrated contextual environment, the students can also develop communication, independence, confidence and initiative, and project management skills [19]. Adding contextual relevance to the project engages the students and makes them feel that the fundamentals are more relevant which results in better retention by students [20]-[22].

2.2. Co-curricular initiatives

Co-curricular activity is seen as “requires a student's participation outside of normal class-room time as a condition for meeting a curricular requirement" [23]. By contrast, extra-curricular activities can be “either academic or non-academic activities that are conducted under the auspices of the school but occur outside of normal classroom time and are not part of the curriculum" [23]. Both of these activities encourage students to become more confident and to develop non-discipline specific knowledge [24],[25].

Students are often unable to animate professional engineering experiences since the pedagogy is more academic and theoretical rather than relevant to industrial design experiences [26]-[30]. Traditional curricula have limited potential for real-world project-based learning opportunities in comparison to integrated curricula and co-curricular activities. Furthermore, some research [5], [31]-[34] suggests aligning pedagogy to authentic industry related/driven projects enhances employability [35].

Fisher [36] commented that co-curricular activities present an opportunity for students to develop professional skills that include teamwork, ethics, communication, life-long learning and the social impact of engineering. Research on the higher level impact on student involvement in specific co-curricular programmes show favourable development of professional and technical skills [37]-[40]. Co-curricular activities, aligned to actual credit-bearing modules, have been linked to an increase in academic emotional engagement through pathways of self-efficacy [41]. If students are given educational freedom they will be able to develop effective self-management strategies to negotiate critical discussions during disagreements on subject knowledge in teams [42].

A wide range of co-curricular programs exist and one such initiative that is closely related to the AREND project (i.e. it is co-curricular, vertically integrated, PBL with industry collaborators) is the Civil Engineering 4 Real (CE4R) initiative; “a co-curricular (evening) initiative that encourages students to utilise prior knowledge from university studies and continual professional development (CPD) by applying them to real-life engineering problem scenarios” [35]. One of the framework-related aspects Murray et al., [35] commented that co-curricular activities run the risk of not scaffolding and supporting new students in the process. However, meaningful learning can occur when the student experiences a gap between what they already know and requirements to solve the problem at hand [43]. Deep learning happens as a consequence of debates amongst students from their different levels of understanding of the knowledge and through these debates arriving at a variety of different solutions [44].

2.3 Vertically integrated projects

Pai et al., [45] defines vertical integration among students as: "provision of information aid and sharing learning roles through all learner stages, where students from higher levels are helping students from lower levels to understand engineering concepts and work collaboratively on projects". Within a vertically integrated project (VIP), students are no longer taking on the role of passive audience but rather of active participants. Fung [46] describes a research-aligned VIP as "the kinds of active, critical and analytic enquiry undertaken by researchers – involving competencies that are difficult to develop through the traditional classroom model of teaching, often referred to as subject-based learning". In addition, a VIP model has the potential to include collaborative working and learning between undergraduates, postgraduates and academic staff [47].

Literature suggests that vertically integrated education has a far greater ability to promote social support when compared with competitive and individualistic forms of education [11],[48]-[52]. Feldman [11] found that vertical integration encouraged deep understanding of conceptual content through continuity of class material and by more student-to-student and faculty-to-student interaction. Strachan et al., [47] mentioned that vertically integrated projects offer a greater opportunity for students to be more experiential and self-directed in their approach to learning.

Al-Zubaidy et al., [53] exposed students at the Heriot-Watt University Dubai Campus to vertical integration. Chin and Yue [54] implemented a vertically-integrated PBL that resembles an industry set-up and facilitates a well-defined environment to foster innovation and communication from the first to the second year [54]. They found that a cohort exposed to integration (compared to one that is not) has an improvement in academic achievement. Strachan et al., [47] at the University of Strathclyde adopted the VIP program approach (initially started at the Georgia Institute of Technology) from the VIP Consortium to align with the United Nations' Sustainable Development Goals (SDG) Agenda 2030. They found that students themselves become supervisory resources by being involved in the projects for consecutive years. Encouraging peer-to-peer learning and mentoring allows for the faculty-student supervision role to become more passive as the project evolves to become more student-centered in its operation. In addition, the practical challenges of vertical and horizontal alignment lead to professional development of the students involved on the projects.

Various institutions have implemented integrated programs either on a co-curricular or curricular level. Some of the most notable efforts have been the Vertically Integrated Projects (VIP) Consortium, of which consists of approximately 35 institutions across the globe. These projects require faculty members to develop teams that are multidisciplinary, vertically-integrated, and long-term and that provide a significant benefit to the faculty member's research program [55]-[57]. At University College London (UCL) the Integrated Engineering Program aligns the undergraduate teaching and learning with their institution's ongoing research portfolio [46]. And at Aalborg University, Denmark they have mega projects that consist of interdisciplinary projects that range across the whole University and involve a large number of students working together [58]. All projects are based on global problems as formulated in the United Nations' 17 SDGs.

2.4. Alignment with faculty roles

Previous studies have shown that faculty who participate in extra- and co-curricular activities report intrinsic benefits of an altruistic nature [59]. Faculty enjoy the personal contact with students and playing a more active part in their development. Although the AREND project experience does not dispute this benefit, more explicit alignment with faculty roles is required to justify the significant mental, emotional and time investments required. Key performance areas for academic faculty centre around research and teaching, where supervision of research straddles these two areas. Senior faculty are also required to attract funding through their research, while community service is emerging as a performance area on all levels.

Moliner et al. [13] investigated the perceptions of professors in an inter-university engineering PBL experience. Some of the concerns of the professors were the increased workload because such initiatives are not usually formally recognized. Also the difficulty of controlling the content that students integrate into their PBL learning experience compared to the uniform learning that is perceived to take place in traditional classes.

3. Co-curricular Framework for Student Involvement

The AREND project evolved into its current co-curricular framework over the past six years. The remainder of this paper summarises this process as well as highlighting some of the challenges and successes in implementing the framework.

3.1. Phase 1: No formal framework at University of Pretoria, multinational, multidisciplinary PBL collaboration with three Universities

The AREND project was initially established as an international team of students at four universities on three continents. The universities were: University of Colorado (CU) Boulder, United States; the Helsinki Metropolia University of Applied Sciences, Finland; the University of Stuttgart (US), Germany; and the University of Pretoria (UP), South Africa. These four teams provided complementary technical skills. The team at University of Pretoria had contact with the Kruger National Park organization.

AREND is a PBL initiative aligned to a real-world challenge with an overarching problem statement:

> *"Team AREND will design a technological solution to aid Kruger National Park (KNP) rangers in the protection of black and white rhinos from poaching. The solution shall constitute, but not be limited to, an unmanned aircraft (18kg, 4.2m wingspan, cruise speed 20m/s, stall speed 15m/s) capable of conducting, efficient, quiet and remote surveillance of large park areas such as KNP. The drone shall be operable from a central base within KNP, have extended flight endurance (~120 min), and be able to detect/distinguish humans and animals with on-board sensors. Design modularity is encouraged."* [60],[61]

The Universities had weekly global conference meetings (60-90min) to report on tasks completed in the independent parts of the project and these were shared through a cloud file system. Quarterly there were milestone/design review meetings where all advisors and sponsors were present and these lasted for several hours and were handled more formally.

In 2014, the team at UP consisted of two actively-engaged, full-time staff members (part-time PhD students) and six volunteer final year students. This structure was very different to the CU and US teams who had dedicated Masters students working in groups for specific credits. The four teams were responsible for specific tasks of which all were dependent on UP to develop the overarching concept of operations to enable design requirements to be formulated. Figure 1 shows the initial framework for the team structure in Phase 1.

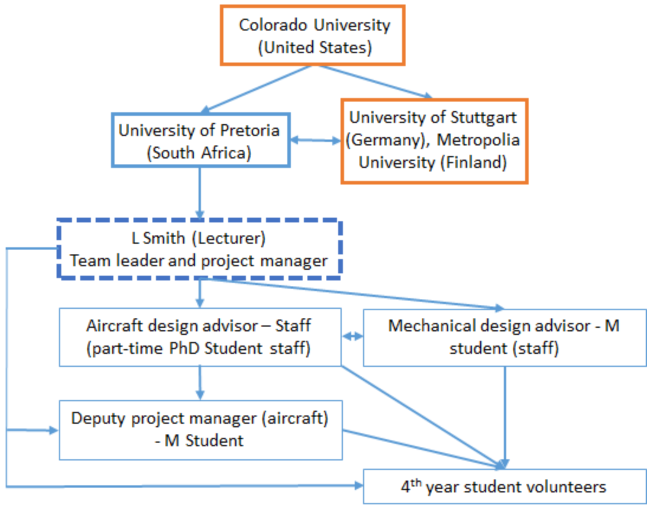

Figure 1: Initial framework for the AREND project.

After the first year, the following reflections led to decisions to ensure more productive student engagement and project sustainability:

- ❑ The setting of the project already made it a multidisciplinary, multinational PBL aligned to real-world initiatives. However at UP there was no formal structure of how such structures could work sustainably.
- ❑ The enthusiasm and self-directed initiative was observed with the volunteers that took part in the project. However, two crucial aspects of the UP context became a challenge. First, the students' curriculum load and timelines and, second, the students' lack of technical and personal skills which hampered their teamwork in a global collaborative project. There was also a concern that the project would not be sustainable if it did not become credit bearing. Also when working in a large international team, students needed to have a clear directive of what part of the work was their responsibility.
- ❑ The two active staff members bore the additional burden of leading the project in addition to completing their PhDs while also dealing with a full teaching load with large cohorts (>300 at least and up to 1300 for one). This did not allow much time for guiding the undergraduate students in the project.

3.2 Phase 2: Small-scale, co-curricular vertical integration with six existing PBL modules with minor collaboration with two international Universities

During 2015, the team leader at UP devised a way to align students' contributions to AREND with the requirements of existing PBL modules in the curriculum so that team members could justifiably dedicate their time to their AREND tasks. The design and development of the various sub-systems and components were divided into modular sub-projects that could meet the requirements of these existing PBL modules. Within Mechanical and Aeronautical Engineering, students could make a sub-project the topic of their final year design project (one semester), their final year research project (two semesters), or use it to satisfy the practical training requirements of the degree (six weeks in their

2nd and 3rd year). Students from other Engineering Departments could also work on sub-projects to fulfill the practical training requirements of their degrees.

Conveniently, the final year projects were then directly assessed for the Engineering Council of South Africa (ECSA) graduate attributes 6 (Professional and technical communication) and 9 (Independent learning ability). However, since the AREND sub-projects were linked to the greater AREND team and supported by the team leader, ECSA graduate attributes 8 (Individual, team and multidisciplinary work), 10 (Engineering professionalism), and 11 (Engineering Management) could also be integrated and facilitated into the students' experience. These last three ECSA graduate attributes were not formally assessed, but the team leader spent time guiding the students on working within a local and international group, with different disciplines and timelines.

Hand-ons manufacturing training and small scale project management (includes safety and ethical concerns) within an industry setting form the basis of the practical training modules requirements. Apart from aligning AREND with the existing curriculum to incentivise student involvement, initial connections with South African industry were also forged in 2015. Students were given the opportunity to learn from industry experts, return to the team with new skills, and take on leadership or self-directed roles. The first 2nd year cohort consisted of six students who completed their training at the Council of Scientific and Industrial Research (CSIR) in composite design, manufacturing, and airframe integration. After this, each of these students were assigned to smaller design and manufacturing portions of the greater project [61].

In order to reduce staff workload, two graduate students (a volunteer from UP and an MSc student from CU) were recruited to act as interim deputy project managers who guided the design decisions with input from the UP staff. In preparation for the integration phase at the end of 2015, three electronic engineering undergraduates were recruited to learn the sub-systems of the UAV. At the end of phase two, the University A team lead came to South Africa and worked with the UP team to finalise the first integration phase. In 2016, the programme was placed on hold when the team leader took a PhD completion sabbatical. The third phase of the programme thus started in 2017 when UP became the main project drivers, with the framework layout shown in Figure 2.

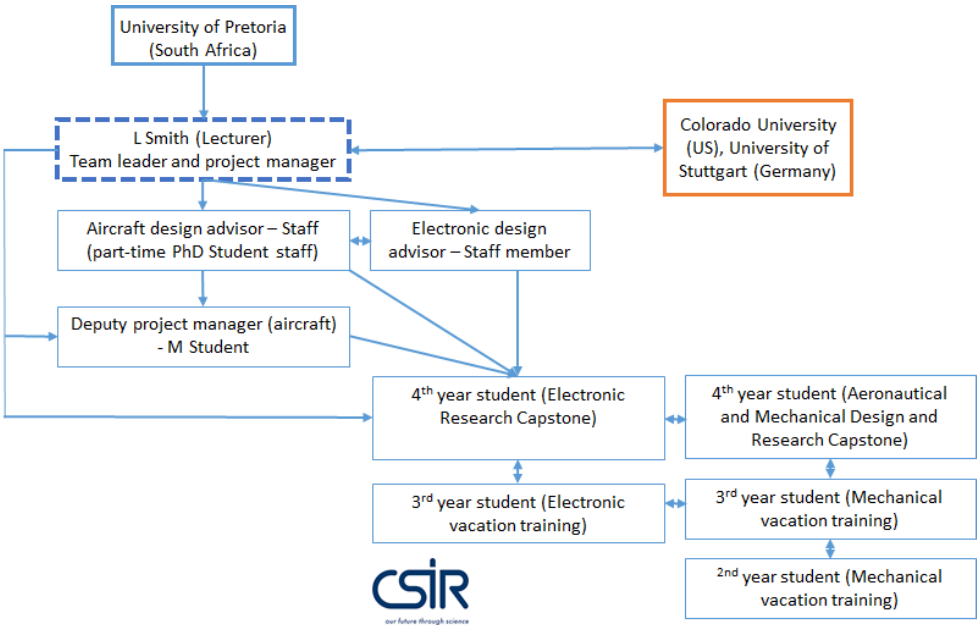

Figure 2: Phase 2 of a vertically integrated, co-curricular framework for project AREND with initial interface to industry.

The AREND project became "something in-between" a co- and extra-curricular activity by differentiating between team members and volunteers. Team members are students whose work on the project feeds into one or more of their curricular requirements, for example practical training hours, senior design projects, or postgraduate research. Volunteers are interested students who contribute to the project for personal benefit unrelated to their current curricular requirements. Repeated experience in the team has shown that volunteers persist for a much shorter period and usually do not contribute as meaningfully.

The project is not formally part of the Mechanical Engineering curriculum, but a "learning pathway" establishes curricular alignment for a student at each academic level by selecting an existing PBL module and completing their course work on AREND. While co-curricular alignment incentivises students, faculty members involved in the AREND project also require incentives to take on the additional work. Although there are intrinsic rewards to being involved in students' growth, aligning faculties' efforts in the programme to their faculty roles would provide a more sustainable incentive. However this was not an option in the School.

3.3 Phase 3: Co-curricular vertical integration with open international collaboration and local industry involvement

In previous phases, a dedicated design advisor prescribed design solutions for sub-projects. This role was scrapped and team members were required to come up with their own design solutions in collaboration with a Masters student who worked closely with the team leader. In 2017, the team was given dedicated lab space on campus which greatly facilitated progress. During the third phase, the structure and curriculum alignment of AREND remained the same as phase two. The important changes that distinguished this phase were the greater design autonomy given to team members, the growth in the size of the AREND team at UP, accommodation of international exchange students in the team, and increased support and mentorship from industry.

The team now consisted of 18 UP students from 2nd to 4th year, one volunteer Masters student at UP, a Masters exchange student from the US, and two 3rd year exchange students from École Nationale Supérieure de Mécanique et d'Aérotechnique (ENSMA) in France. The students were divided into smaller groups, each dedicated to larger complex subsystems. Some more mature students and the Masters students remained involved across sub-teams to ensure coherence of the overall system.

Students in the second year of their degree could enter the AREND project and not only see a full scale engineering project, but understand how all the currently isolated subject matter interfaces. Thermodynamics, dynamics, materials, manufacturing and design, and electronics all become part of an actual final product in the drone that team AREND develops. Students were teamed up with older students in their 3rd and 4th year of study as well as international Master students. This brought different skills, knowledge and maturity to the project. The second year students' projects were low in complexity and more related to hands-on manufacturing training and graphical communication within their sub-project. The 3rd year students were involved in the coordination and management of sub-projects and teams in addition to having their own small design tasks. Final years used their capstone design or research project to develop full sub-systems for the project. Their projects became the sub-projects and they were assigned their own teams. The early integration and scaffolding of project complexity and synthesis, better prepared the final years for their capstone design and research projects. Figure 3 shows the final framework for the team structure in Phase 3, and it is still the current working framework.

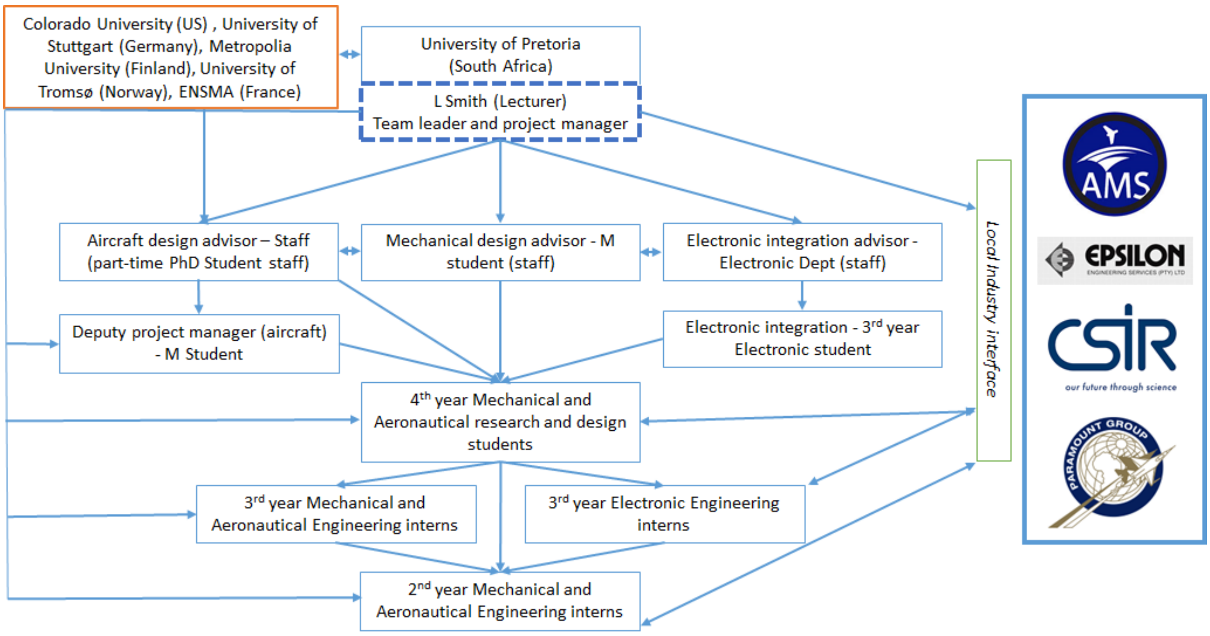

Figure 3: Current working vertically integrated, co-curricular framework for project AREND.

As the initial project funding (through a Kickstarter initiative) was running out, the team leader focused on obtaining project funds and mentorship from local industry. The CSIR again offered short internships during which team members manufactured some of the smaller parts of the UAV. Epsilon Engineering also came on-board to offer internships during which team members made larger parts of the fuselage. Aerial Monitoring Solutions (AMS) played a mentoring role as their entire engineering team worked with the AREND team members to help them prepare for flight testing and ensure that all integration phases were ready. Paramount also mentored the team by assisting with the formal paperwork procedure required to ensure safe and legal flight testing. Both Paramount and AMS spent all flight testing days with the team. The team not only had the opportunity to learn from experienced engineers, but also built a network of local aviation industry contacts for their future careers.

The team in this phase of the project were involved in many failed attempts to fly the AREND drone. Many of these failures led to students developing additional sub-projects and ensuring that flight plans are documented in as detailed a manner as possible. Halfway through the year, the team had their first successful powered flight (without the expensive embedded systems on board) leaving the project with a new wider scope of projects moving forward. One being to change the configuration of the aircraft and the other to develop an on-board test platform for different sensor packages.

At the end of the third phase, most of the work happened in productive spurts during university recesses with only those students who were using their AREND work for design and research projects in Mechanical and Aeronautical Engineering working throughout the semester. Although the recess-bound work rhythm provided dedicated and productive time, it had two drawbacks. By losing momentum throughout the semester, many students had to be "brought up to speed" at the start of the recess. In addition, the team leader no longer had any breaks from academic duties and was now working full time during the semesters and the recesses. The size of the team and its high member turnover also placed great strain on the team leader, who fulfilled many leadership roles on the team and served as the source of institutional memory.

To find a solution to the sporadic work rhythm and the mental and emotional burden on the team leader, AREND experimented with becoming one of the teams on the newly formed Vertically Integrated Projects (VIP) platform at UP.

3.4 Phase 4: Transition to the VIP structure, no collaboration with international Universities

The VIP programme started at UP in February 2018, making UP the first site in Africa to become part of the global VIP Consortium. Faculty-led vertically integrated teams (called VIP teams) were established and project AREND became one of the teams on this platform. The potential of a faculty-wide programme could lead to efforts such as project AREND to be formally incorporated into faculty roles which in turn would solve the problem observed in phase 2 of sustainable incentive for faculty members.

The VIP ethos prescribes curriculum alignment as a necessity, either by registering VIP teams as free or technical electives to a degree, or by making it "credit-bearing" in some other way. It seemed that the structure embedded in the VIP model would enable volunteers from many other disciplines to also become part of AREND and would inspire consistent work throughout the semester. Although the intention of the transition to that of the VIP team was well communicated and supported by the team, there was great resistance when it came to the actual implementation. Non-negotiables of the VIP model include weekly progress meetings, continuous documentation (by means of design notebooks and team wikis) and individual performance reviews. All three of these criteria proved to be major stumbling blocks for the AREND team. The team leader was abroad on a research trip for most of the second semester of 2018 and thus with their leader absent, the team mostly ignored the VIP integration altogether. Upon the team leaders return in 2019, commitment to the VIP integration was resuscitated. After another six months the team leader concluded that even the VIP platform was not capable of shifting the workload from recesses into the semester.

Even though the AREND team could not integrate with VIP, there were valuable outcomes from the attempt to integrate. The team recognized the benefits of starting on the project that is so big, feeling overwhelmed, and finding your feet within a sub-system. However, the wiki page from VIP inspired them to develop their own equivalent wiki and repository for students starting on the project to integrate more effortlessly. In addition, this became a historic view of the project, where students not only see who was on the project (which the team had before) but rather what decisions were made and why.

By the start of the fourth phase only the international collaboration with US remained. New relationships were being formed with ENSMA (France) and University of Tromsø (UiT) (Norway). At the end of 2019, two new Master students from US and UiT arrived tasked with developing a new aircraft configuration. This new objective created many new and exciting sub-projects for undergraduates to become involved in.

3.5 Phase 5: Reflections on Phases 1-4 and exploring a project-aligned curriculum

The team leader of project AREND's incentive to remain on the project is largely due to personal passion for effective and sustained integrative curricula. At UP, staff training and resources are limited and large cohorts inhibit conventionally described PBL initiatives where cohorts are less than 100. AREND has given the team leader opportunities to explore PBL in a small group (< 30) and trade-off between the limitations and challenges within the existing curriculum structure in the Engineering School to develop a sustainable large scale project aligned curriculum proposal. A two-phase plan to explore large-scale transition of an AREND-type structure at UP will be the next step in the process.

First, the dissemination of the lessons learnt and the experience of the students involved in AREND over the last six years will be completed using surveys and interviews. This will give a clear indication of the developmental benefits students working on AREND obtained in comparison to a large cohort that does not participate in such programmes.

Second, staff need to be trained for PBL-specific education to enable them to understand the learning potential of an integrated PBL structure and aid in solving the possible pitfalls in PBL with large cohorts. Then research groups within the Department can develop themes from which central projects would emerge. AREND would become an example of the Aeronautical Research group, while another existing project could become a similar prototype for the Vehicle Dynamics Group. Essentially the other research groups can be assisted to develop similar projects.

The lecturers in the design stream of the department will take ownership of the integration and large scale design projects. Each semester through the four years would have one staff member responsible for design. They would become group leaders per semester to develop integrated practical and work assignments relating to the larger vertically-integrated project.

Ideally, this would lead to two benefits: 1) students have an integrated understanding of currently silo-ed course material through four themes, and 2) they could be developed into more productive postgraduate students due to the alignment with larger research projects. In addition, the professional skill development associated with PBL can lead to students being more employable when leaving UP.

4. Limitations and implications for future research

Currently the work exists and is conveyed from a single perspective. The impact of this framework will be validated through interviews with AREND alumni and their employees to determine the true value of these projects. Determining the relevance of the impact of this framework to the practices of engineering education, requires more data and investigation to be performed. In particular, we are interested in the student experience and the students' perception of ARENDs contribution to their professional skill development and subject cross synthesis. Based on the above findings, administrators at engineering schools and colleges should consider expanding support for student- and staff-driven co-curricular programming.

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