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Execution of the C-D-I-O framework at postgraduate level in mechanical engineering

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Abstract

The usage of the Conceive-Design-Implement-Operate or C-D-I-O initiative is well documented within the context of engineering undergraduate programmes. To date, there are over 140 universities around the world which are part of the initiative, and most, if not all, of these universities have utilised the initiative as a framework within undergraduate curricula. This has been initially done for engineering undergraduate programmes, with other disciplines (outside of engineering) now choosing to implement this framework within its own context – due to its success in enhancing the overall student learning experience, at the engineering undergraduate level. There are, however, limited studies on how the framework is utilised within the context of a postgraduate programme. In particular, there are little to no studies on how this framework may be utilised to enhance the student learning experience within research-based postgraduate programmes e.g. MSc (by research) or PhD programmes. This paper aims to firstly review the available literature on how the framework influences postgraduate programmes globally. An attempt would also be made to discuss how previous studies have applied the framework to postgraduate education. To further narrate the application of the framework to graduate studies, a case study of a research-mode MSc programme will be explored. Specifically, how C-D-I-O influenced

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the research methodology of a chosen project within the MSc and resulted in designing and building an engineering system in a systematic and structured manner.

Keywords
C-D-I-O, mechanical engineering, postgraduate level

Introduction

In 1997, the C-D-I-O initiative was established in the areas of engineering education and is a well-known framework that has yielded positive results in producing engineers that are able to develop solutions for societies' challenges. The C-D-I-O initiative was incepted in 2001, while later in 2004, its standards were designed and established. The Queen's University in Canada held the first conference on C-D-I-O a year later, and over just 10 years, more than 100 schools across the globe adopted the initiative in their programs.[1] The initiative has emerged into institutions of higher education in Russia since 2010 and later on became a widespread approach across the country. In 2013, Skolkovo Institute of Science and Technology established a CPD programme in collaboration with universities in Sweden, Netherlands, Denmark and USA. The programme was based on C-D-I-O standards that assisted the university academicians to properly implement the C-D-I-O methodology. Later in 2016, the aforementioned CPD programme went online and was delivered via a massive open online course focusing on how to implement the C-D-I-O standards in Engineering Education.[2] Malmqvist et al.[3] evaluated the effectiveness, benefits and limitations of the C-D-I-O approach via a survey that was participated by 47 universities from 22 countries. The study showed that mechanical, electrical and computer-engineering programs implemented C-D-I-O the most followed by industrial, civil and chemical engineering. Participants had found C-D-I-O to be a systematic way for the design and implementation of engineering education. Feedback showed that the initiative (or framework) had huge impact on students' experience and satisfaction by helping them to improve their design thinking as well as conceiving (or brainstorming) skills and employability. There is therefore a large body of research that supports the execution of the framework within the context of an engineering undergraduate programme, and more recently, undergraduate programmes of differing disciplines – e.g. business, accountancy, etc. The fact that the framework has transcended the boundaries of engineering education is testament in its ability to allow flexibility in terms of its implementation for various disciplines. There are, however, minimal studies that examine the impact the framework has on postgraduate education. The following section provides some insight into the available work in literature, where educators have made efforts to embed C-D-I-O within postgraduate programmes.

Literature summary

Kozanitis et al.[4] discussed approaches of five institutions of higher learning from Singapore, Ireland, Canada, Sweden and the United States which implemented the framework to train and enhance their educators teaching and learning skills in line with C-D-I-O practices. Amongst all, Queen's University of Belfast employed the C-D-I-O framework to enrich the quality of a postgraduate in a higher education teaching programme. With the priority given to new recruits and those on probation, it focused on enhancing pedagogical methods including teaching, learning and student assessment. The evaluation of the staff enrolled into the course was highly reliant on the reflection of teaching methods such as teaching journals and portfolios, evaluation of examination techniques, a case-based project on rectifying students learning challenges, as well as reciprocal class visitations amongst the staff. The programme was successfully implemented and upheld the teaching excellence of the faculty.

Helenius[5] elaborated on a new master's programme in service design and engineering that was established based on the insights from industry executives and the C-D-I-O syllabus. The programme was created to address the needs of the nation in the areas of engineering, design and social systems. The research showed that the programme syllabus was aligned with the framework; however, the authors suggested adding five new elements to the framework to fulfil the requirements for a master's study. The new elements dealt with internships, scientific publishing, leadership of systems and processes, entrepreneurship and impact of their knowledge to the society. The aforementioned programme was deemed as an innovative initiative within the university.

Karltun and Berglund[6] studied a multidisciplinary approach based on the framework which was applied to a master's programme in Ergonomics and Human-Technology-Organization, and discussed the lessons learnt. Students enrolled into the programme were from different backgrounds, such as engineering, psychology, social science and ergonomics. Questionnaires showed that students were happy with the programmes, believing that the programmes had enhanced the breadth and depth of their understanding leading to a positive impact to their personal as well as professional life. One student mentioned that he learnt to work with people from different educational and cultural backgrounds in a team, similar to what normally happens in many real-world scenarios. The multidisciplinary approach provided an avenue for students to understand and appreciate the cultural differences existing in different educational disciplines.

Jian-Hua et al.[7] suggested establishing a university-industry laboratory to train engineering master students in line with C-D-I-O. They mentioned that the core purpose of C-D-I-O is to apply the knowledge into practice, and the laboratory provides a venue for master students dealing with industrial projects. They can test skills and improve on their weaknesses prior to joining the job market upon graduation. Authors also mentioned that working in the lab may also help to train young academic staff, since they are involved in industrial-related projects and may learn about the best practices as well as the demands from industry.

Yongxin et al.[8] explored how C-D-I-O may enrich the educational pathway for professional degree graduate students or practical engineering master students. They elaborated that the concepts of project design, planning and execution that are studied in the C-D-I-O framework have improved the capabilities of master students and made them ready to face the complex challenges.

Chuchalin et al.[9] evaluated the implementation of the C-D-I-O syllabus to the design of undergraduate as well as master and PhD programmes. They mentioned that the master's programme was mainly focusing on the design and development of new engineering systems and processes that have a positive impact on human life. Therefore, half of the leaning outcomes of the programme were related to 'Design', while the other half were equally divided between 'Conceive' and 'Implement and Operate'. This emphasis was different for the PhD programme with 65% of competencies dealing with 'Conceive', 25% to 'Design' and the remaining 10% were attributed to 'Implement and Operate'. The authors suggested to adjust the C-D-I-O syllabus to the learning outcomes of the undergraduate and the two postgraduate programmes. They also believed that items 2.1 to 2.3 of Version 2 of the C-D-I-O syllabus, namely: analytical reasoning and problem solving, experimentation and knowledge discovery, and system thinking, were more aligned to the requirements of postgraduate programmes rather than the undergraduates.

Antokhina et al.[10] made use of C-D-I-O to enrich the quality of projects run under master programmes. They implemented the approach to two programmes, namely: Embedded Systems for the Information Processing and Control and System Researchers for the Control Tasks. A multidisciplinary project was jointly offered to both programmes, whereby one worked on the hardware part and the other focused on software development. Real-world projects from the space industry were given to the students, so that it could form the basis for the students' thesis later. The practice was very beneficial to the students, as they were able to combine theories with industrial practice. It also helped faculty to create collaboration networks with new industrial partners.

Ding et al.[11] proposed a new teaching approach for postgraduate engineering students based on the combination of three education techniques; C-D-I-O, Project-Based and Integration Teaching. They observed that the suggested approach had improved the learning of postgraduate students in terms of their hands-on skills, innovation and ability to engage with research activities. Students were very happy with the new practice as it also affected their employability positively.

Chuchalin et al.[12] and Chuchalin[13] developed new C-D-I-O standards focusing on master and PhD programmes in the areas of food production technology. They mentioned that the conventional C-D-I-O standards were centred on the graduate attributes of bachelor programmes, for example, students' ability to deal with complex engineering challenges. The new standards were aimed at research and innovation aspects that were essential for all master and PhD graduates. The authors elaborated that the newly proposed standards may ensure the continuity and consistency of study from the first degree to the PhD.

Table 1 summarises the previous studies about the application of the C-D-I-O framework for postgraduate engineering programmes and the corresponding findings.

As a collection of work, focusing on the applicability of the framework to postgraduate education, it may be concluded that the implementation of the framework at postgraduate level yields similar, positive results in terms of improving the knowledge and skills of students, and hence enhancing the overall student learning experience. It is also noted that educators outside of the realm of engineering who were bold enough to implement the framework within their own disciplines, also observed a yield of positive sentiments. The work reviewed also argues that the application of the framework has helped to embed various vital abilities in graduates, from teaching and research to leadership and entrepreneurship, and made them better people both in their personal and professional life. Students were able to gauge their capabilities, enhance their problem solving skills and prepare them to work in academia and industry upon graduation. Some of the programmes were only focused on a single discipline with or without industrial collaboration, while some others were multidisciplinary and showed how the C-D-I-O approach was successful for implementation in multidisciplinary programmes.

It was, however, observed that a more detailed study would be required on how the framework may be executed within an actual research project at postgraduate level – specifically, if one was keen on embedding the framework at the level of postgraduate research, how would this be accomplished? Thus, it leads us to the research design of this investigation.

- The main research question driving this investigation is – to what extent can C-D-I-O be successfully applied to postgraduate research within the context of engineering education?
- The objective of the study would then be – *to implement C-D-I-O in postgraduate research within the context of engineering education* and finally,
- The hypothesis would be – *C-D-I-O may be embedded within the research methodology of a postgraduate programme (by research) within the context of engineering education to enhance the overall student learning experience*.

In order to answer the research question, execute the objective and confirm the hypothesis, the authors will narrate their own experience in the form of a case study where the framework has been embedded into a postgraduate research project. The authors will study how the framework was made part of the overall research methodology and provide insight from the perspective of the student whose project involved the framework. As such, the research participants are the students whose project involved the framework as well as the students' supervisory

Table 1. Literature review summary.

Investigation	Areas of application	Findings
Using C-D-I-O framework to enrich the quality of a programme[1]	Postgraduate in higher education teaching programme	The programme was successfully implemented and upheld the teaching excellence of the faculty
Combination of C-D-I-O syllabus and insights from industry[2]	Master's programme in service design and engineering	Strong focus on internships, scientific publishing, leadership, entrepreneurship, and impact to the society
Multidisciplinary approach based on C-D-I-O framework[3]	Master's programme in Ergonomics and Human-Technology-Organization	Enhanced the breadth and depth of student's understanding, led to positive impact to personal as well as professional life
Implementation of C-D-I-O principles[4]	University-industry laboratory to train engineering master students	Students could test skills and improve on their weaknesses prior to joining the job market upon graduation
Application of C-D-I-O framework[5]	Professional degree graduate students or practical engineering masters	Made students ready to face the complex world challenges in the field
Evaluating the implementation of C-D-I-O syllabus[6]	Design of master and PhD programmes	Authors advised to place more emphasis on analytical reasoning and problem solving, experimentation and knowledge discovery, and system thinking
To make use of C-D-I-O practice[7]	To enhance the quality of projects run under two master programmes	Students were able to combine theories with industrial practice
To combine C-D-I-O, project-based and Integration teaching as a new teaching approach[8]	Postgraduate engineering students	Improved the hands-on skills, innovation, ability to engage with research activities, and employability
Development of new C-D-I-O standards[9,10]	Master and PhD programmes in the area of food production technology	Enhancement of students' ability in research and innovation

C-D-I-O: Conceive-Design-Implement-Operate.

committee. In order to support the research design, feedback will be provided by the research participants and this represents their perspective on whether the application of the framework within the context of postgraduate education was a success in enhancing the students' learning experience.

Case study

The Master of Science in Engineering at Taylor's University (or MSc) is a postgraduate programme in full research mode. The structure of the programme is as follows. The Master of Science in Engineering programme at Taylor's School of Engineering commenced in 2011 as a research-based programme and the very first batch of students graduated in 2013. To prepare students for their research work, two one-credit modules called 'Research Methods for Science' and 'Quantitative Data Analysis' were offered to the students. They are required to pass a thesis proposal defence, which serves as a gauge of the students' preparation to undertake a research project. Completion of the project within the specific timeline agreed in the thesis proposal defence is a vital part of the candidature. Students and their supervisors must have a clear understanding of how the research project should progress. At different stages of their progress, students were exposed to a variety of skills and training opportunities. It is compulsory for students to present their findings in an engineering research conference, which is organised twice a year by the school. Attendance and presentation in conferences will give students valuable opportunities for research exposure and professional networking. Some of the students were also involved in educating undergraduate students as teaching assistants and tutors, and this participation can help to develop their teaching and learning skills. The aim/objective and programme learning outcomes of the aforementioned master programme are as follows:

Aim/Objective:

- Equip students with an expanded mental capacity capable of handling complex systems necessary for a career in R&D, PhD study or general career advancement.

Programme Learning outcomes:

1. Demonstrate mastery of knowledge in the selected field of research and recognise its significance in the global context
2. Demonstrate ability to think critically and creatively
3. Be able to plan and conduct research independently using appropriate tools
4. Adhere to the relevant ethical and professional codes of practice
5. Disseminate research findings through peer reviewed publication and oral presentation
6. Exhibit technical and team leadership capabilities
7. Appreciate the need for continual professional development

Each MSc student would be provided with a postgraduate research project of sufficient complexity to ensure that they are able to achieve the programme aims, objectives and learning outcomes. In this particular case, the project was entitled 'An Optimal Aerodynamic Design for a Sustainable Human Powered Vehicle'.

Background on sustainability and the velomobile (human powered vehicle)

The following section provides an introduction to what is a human powered vehicle (HPV). It presents a summarised narrative on the background as well as the need on why such mode of transportation is required, prior to the application of the C-D-I-O framework to design and build one as part of a postgraduate project.

Nowadays, the significance of sustainability is becoming increasingly clear to the public eye as well as an important consideration for engineering projects. Ensuring that the needs of the present are met without compromising on the ability for future generations to meet their own needs covers various fields of research, and as time moves on, those needs may even change depending on what the future holds. However, one need that must always be met – be it in the past, present or future – is transportation: the ability to go from point A to point B.

One such vehicle that comes close to the ideal for sustainability is the *velomobile*. A velomobile is defined as an HPV with a full aerodynamic fairing Van de Walle.[14] Being human powered, it consumes a resource that is often times said to be underutilised yet readily available; human power, and the only emission of human power is an insignificant amount of carbon dioxide relative to what current methods of transportation emit (which contributes to goal 12 of the UN sustainable development goals, 'responsible consumption and production'). A few examples of velomobiles are shown in Figure 1.

There are broadly two ways to approach aerodynamic design for land vehicles. One is the ground-up approach, where the main body is shaped for low drag first before the other non-aerodynamic elements are designed within those constraints. The other is the improvement approach, which starts with a vehicle design that satisfies the non-aerodynamic constraints and 'finesses the details to lower the drag as much as practical'.[15]

This research study is mainly about having sustainability considerations with a focus on aerodynamics, which sets it apart from the other studies done in the velomobile field. The focus of the study was to create an optimal aerodynamic design for a sustainable HPV for everyday use.

Research methodology of the postgraduate project

Before delving deeper into this section, it should be clarified that this section represents the research methodology employed within the students' postgraduate project and *not* the research methodology of the present investigation, i.e. one that uses the case study approach.

The overarching structure of the research methodology employed in this study is Conceive, Design, Implement and Operate (C-D-I-O), as shown in Figure 2.

The next four subsections narrate what is accomplished at each stage of the C-D-I-O framework, as the research team proceeds to design and build an HPV.

Figure 1. Examples of velomobiles.[14]

Conceive. At the conceiving stage, a deep understanding of the research topic/challenge to be addressed is required Al-Atabi.[16] The focus of the study was to create an optimal aerodynamic design for a sustainable HPV for everyday use; therefore, an extensive literature review (as shown in the literature review section) of all aspects of velomobile and general HPV designs is done.

At this stage, the main high-level design concept of the HPV is established. The design considerations for sustainability and aerodynamics have to be addressed at the same time. In order for an HPV to be practical for everyday use, the aspects of sustainability should be considered first in order to create the 'base HPV', which sets the constraints of the aerodynamic fairing. At the same time, the 'base HPV' should be one that has a high potential to produce an aerodynamically efficient design, i.e. it should readily accommodate a streamlined shape with as little flow separation as possible in order to produce the lowest amount of drag. In order to achieve this, a decision matrix (also known as the Pugh method) is utilised.[17]

The 'base HPV' to choose that fits the requirements for both sustainability and aerodynamics can be defined as the wheel configuration of the HPV, i.e. how the wheels are arranged around the rider.

Another note is that having a fairing is always better than not having a fairing, for both aerodynamic advantages (as stated in Alam et al.[18]) and practicality advantages in terms of weather and crash protection. The velomobile should in

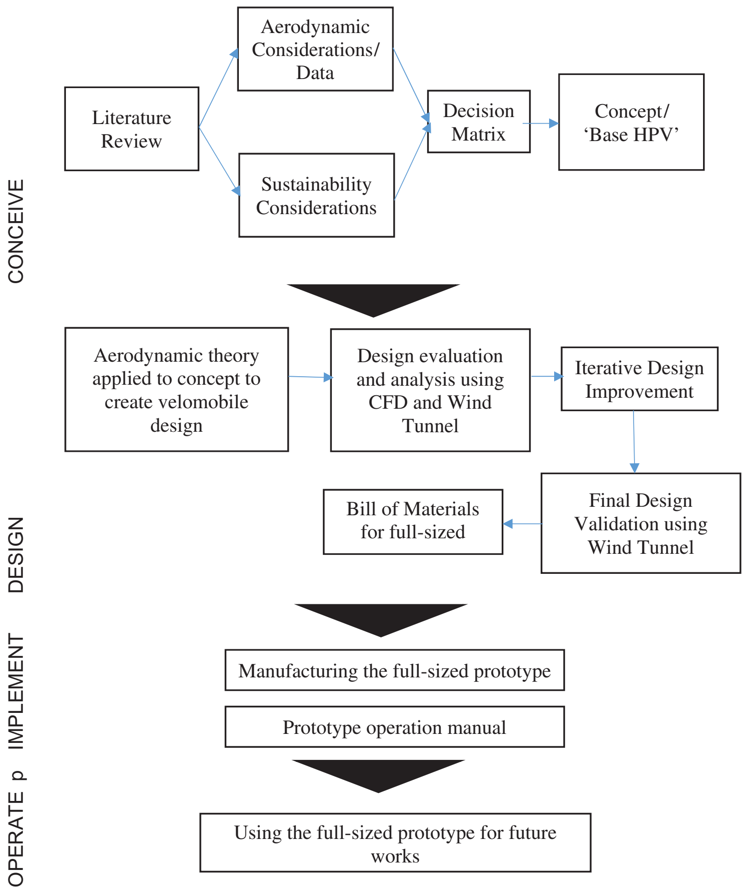

Figure 2. C-D-I-O flowchart.

fact be in another class of vehicle distinct from the bicycle (as stated in Van de Walle[14]). The conventional bicycle was, however, still included in the decision matrix as a sort of 'control' as it is what most of the general public associate with as a HPV.

For sustainability, the three pillars (social, economic and environment) should be weighted equally, as they are interdependent on each other (as observed in Adams[19]). As most literature that pertains to both velomobiles and sustainability describe the sustainability benefits of velomobiles in general (rather than being specific to each of the aforementioned categories), inferential logic is utilised based on that in order to rank the categories. The summary of that is shown in Table 2.

For aerodynamics, the only metric to be used is the drag coefficient, C_D (at 0 degrees AoA).

Table 2. Pillars of sustainability and how they relate to HPVs.

Pillar	How the pillar relates to aerodynamic HPVs
Environmental	• Zero emissions are a given since they utilize human power • A configuration that uses less materials will score higher (management of human consumption of resources) – Daly[20]
Economical	• Cost (can be inferred from amount of materials used).
Social	• Human health benefits of cycling are a given as the power source is human power (i.e. all categories are equal) • Attractive to environmentally-conscious individuals in a practical manner – Black and Cherrier[21]; • Practicality utility

HPV: human powered vehicle.

The 'base HPV' to choose the requirements that fits for both sustainability and aerodynamics can be defined as the wheel configuration of the HPV, i.e. how the wheels are arranged around the rider. There are various esoteric wheel configurations that can be conceived according to Tamai;[15] however, the most proven and practical ones (as found from the literature review) should be chosen and compared in the decision matrix. The wheel configurations chosen for the base HPV are shown in Figure 3. The conventional bicycle is included as well as a control.

Table 3 shows the rankings of each of the categories (as defined in Figure 2) for each criterion (as defined in Table 2) as well as an explanation for why they are ranked in their respective positions (six being the highest rank, one being the lowest).

Thus, the decision matrix for the conceiving stage is shown in Table 4. As each of the pillars of sustainability were interdependent, they are as such given equal weighting. As aerodynamics was a priority in this study, it was given a larger weighting. A conventional bicycle was included as a control. As there were six concepts/wheel configurations to compare, they were ranked from 6 as the highest score, to 1 as the lowest score.

From the decision matrix, the highest scoring concept/wheel configuration was the Tadpole with fairing. Therefore, it was chosen as the base HPV upon which the aerodynamic design was based upon. From this, two concept sketches are shown in Figure 4, which essentially represented the design hypotheses for this research study.

Design. The previous sub-section detailed the 'Conceive' stage of the C-D-I-O framework. Upon the completion of the previous stage, through the culmination of a structured and thought out decision matrix, the next step would be to enter the 'Design' stage and produce viable design concepts for the HPV.

The design process is by nature iterative and covers both the super-system (the overall HPV) and sub-systems (the various parts of the HPV). From the concepts

Figure 3. Base HPV Configurations: Conventional Bicycle, Conventional Bicycle with Partial Fairing, Recumbent two-wheeler with fairing, tadpole with fairing (Rotovelo and Trisled[22]), delta (shown without fairing) (see Horwitz[23]) and four-wheeler with fairing.
CB: conventional bicycle; CBf: conventional bicycle with partial fairing; 2Wf: recumbent 2-wheeler with fairing; Tf: tadpole with fairing; Df: delta with fairing; 4Wf: four-wheeler with fairing.

conceived at the Conceiving stage, the A-C-I-D (system Architecture, Configuration, Integrated and Detailed) design methodology was employed, summarized in Table 5. The drag coefficient is calculated for each case and shown in Table 6.

Implement and operate. To implement means to 'put (a decision, plan, agreement, etc.) into effect', which for this research study means to manage and coordinate various resources to building the prototype. This mainly includes finding and commissioning a service to fabricate the prototype. The operation of the full-size prototype, in the context of this research project, was the production of an

Table 3. HPV Category rankings for each criterion and explanation.

Attribute		Rank	Category	Explanation
C_D		6	2Wf	Lowest average C_D according to data
		5	Tf	Lowest average C_D according to data, however, the range is wide and the higher drag models from data are in the same league with Df and 4Wf
		4	Df	Should produce higher drag than Tf due to not readily conforming to the streamlined teardrop shape. Reliability is limited.
		3	4Wf	The use of more wheels leads to higher drag; however, the full fairing should allow it to have lower drag than unfaired and partially faired HPVs below.
		2	CBf	Limited data because of its limited use.
		1	CB	Most data points, but even the best case with the lowest drag, has higher drag than the worst case for any category with a full fairing.
Sustainability	Environmental	6	CB	Uses the least amount of materials
		5	CBf	The partial fairing is a simple add-on to any conventional bicycle
		4	Df	Uses slightly less material than tadpole due to the simpler design
		3	Tf	Uses slightly more material than delta due to having a more complex steering system
		2	4Wf	Logically uses the most material due to having four wheels and the design complexity/materials that follow
		1	2Wf	Technically uses less materials than the other fully faired categories; however, most of the examples (high-speed vehicles designed to attempt breaking the land record) use advanced materials such as carbon fibre.
	Social	6	CB	Already widely accepted and used by society
		5	CBf	Does not provide much more practicality over the conventional bicycle (same luggage space, lack of static stability). However, being a simple add-on rather than an entirely new vehicle might encourage environmentally conscious people to attach it to their bicycles.
		4	4Wf	Highest practicality as four wheels provide static stability, safer handling than the three-wheel categories, and luggage space

(continued)

Table 3. Continued.

Attribute		Rank	Category	Explanation
		3	Tf	Slightly worse than 4Wf for all the points above(however, most current velomobiles use this configuration)
		2	Df	The one front wheel and two rear wheels provide potentially unsafe handling and worse braking than the tadpole[23]
		1	2Wf	Least practical, as it has no static stability and lack of luggage space
	Economical	6	CB	Least amount of materials as it uses no fairing
		5	CBf	The partial fairing is a small add-on, there is only slightly more material used than in a conventional bicycle.
		4	Tf	The default configuration used by most manufacturers today makes it a proven category.In terms of material costs, it is almost the same as delta; however, it has a slightly more complex design
		3	Df	Actually, almost tied with Tf, but its design is slightly less complex making the cost lower.
		2	4Wf	Uses the most materials out of all the fully faired categories.
		1	2Wf	Technically uses the smallest amount of materials among the categories with full fairings; however, the cost of the existing examples has been very high as they are specialized vehicles designed to be as fast as possible

HPV: human powered vehicle.

Table 4. The conception decision matrix.

	Sustainability				
Categories	Environment	Social	Economics	C_D	Totals
Weightage	1	1	1	2	
Conventional bicycle	6	6	6	1	20
Conventional bicycle with partial fairing	5	5	5	2	19
Recumbent two-wheeler with fairing	1	1	1	6	15
Tadpole with fairing	3	3	4	5	20
Delta with fairing	4	2	3	4	17
Four-wheeler with fairing	2	4	2	3	14

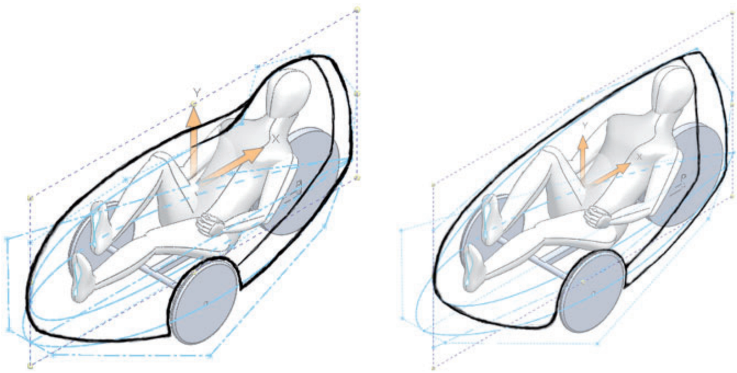

Figure 4. Concept velomobiles.

Table 5. A-C-I-D design.

System architecture design	• Consisted of the main components and product (the various parts of the HPV and the overall HPV) necessary to deliver the requirements (an optimal aerodynamic design for a sustainable HPV). • At this stage, decisions about high-level aspects of the design were set.
Configuration design	• Decisions about the forms and function • For this research study, this involves CFD simulations as well as wind tunnel testing on the (primarily aerodynamic) design of the HPV.
Integrated design	• Interaction between the different parts of the velomobile which comprise the entire system. Ensure that every element of the system works with every other.
Detailed design	• Bill of materials for prototype manufacture.

HPV: human powered vehicle; CFD: computational fluid dynamics.

operating manual for it. It would include details of how to operate the vehicle as well as safety precautions for those who intend to use it for future work.

With the close of the last subsection 'Implement and operate', a detailed description on what occurred throughout the design process, utilising the C-D-I-O framework, was provided. The discussion now focuses on testing the design concepts that were produced as a result of the framework when applied to the design process

Results

As described in the 'Research methodology of the postgraduate project' section earlier, it would be necessary to first test the design concepts numerically and then experimentally, to determine whether an iterative step is necessary for a re-design.

Table 6. Drag coefficient – numerical results.

Case	Drag coefficient
A	0.495
B	0.497

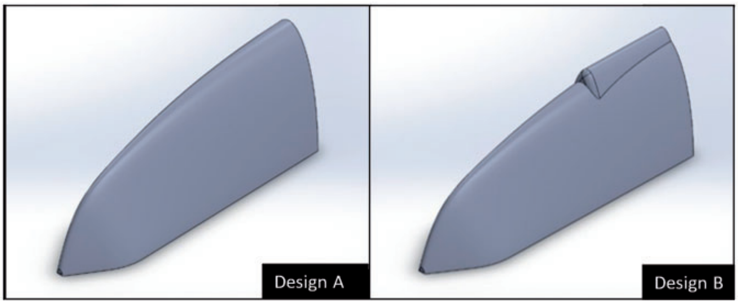

Figure 5. Fairing configurations.

The models were named accordingly and are illustrated in Figure 5.

- Case A: Curved top
- Case B: Curved top with head compartment.

Numerical results. The models were then imported to a numerical software, and a uniform enclosure of 0.2 m was made for the air, which then subtracted the electronic drawing using a Boolean operation. Thus, we were left with a box of air surrounding the model. Then, a meshing of element size of 0.006 m was completed. The value was chosen, as it did not produce too many elements for the computer while still being smaller than the default. A quadratic element order was used as well to acquire the node at the centre of the mesh to better simulate air. A realizable k-ε model was used, as it was a stable equation and suitable for streamline flow. Second-order upwind was used for turbulent kinetic energy and turbulent dissipation rate for better accuracy. The input air was 13 m/s to simulate the operational speed of about 50 km/h of the HPV. Second order was used to gain a more accurate result for the simulation. The drag force value that was relevant is the final one, as the early iterations are yet to converge. As it is impossible to obtain the accurate value from the graphical plot, the report file was used to obtain the final drag force value. The velocity contours of all four models are illustrated in Figure 6.

There is a bigger region of slow air in front of the nose for Cases A and B, indicating a bigger area that air is not able to flow smoothly across the face of the

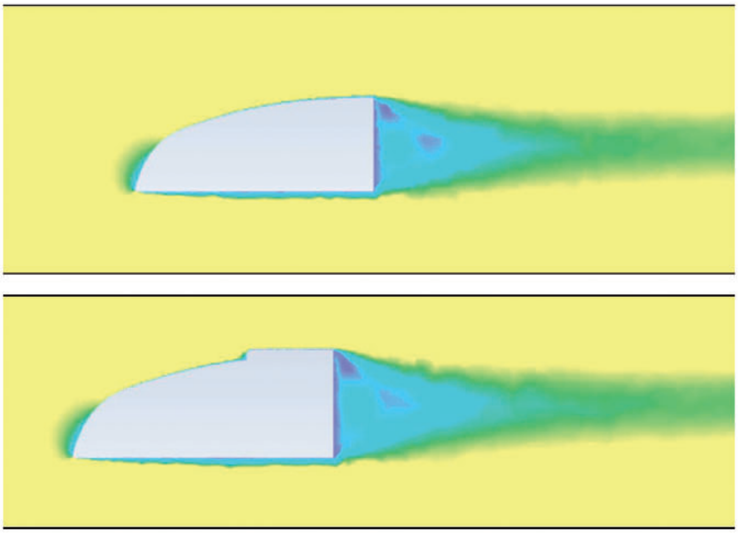

Figure 6. Velocity contours of models A and B.

HPV. From these numerical test result values, the case which experiences the least drag force is that of Case A which has a flat head. The head compartment case provided an increase in drag coefficient but only of about 0.002. This is due to low speeds being experienced and its streamlined shape. The drag coefficient follows the same trend as well. Drag coefficient values obtained from the report file were as follows.

Experimental results. Aerodynamic characteristics of the same two different HPV fairing configurations were investigated by also conducting wind tunnel experiments on the test models. The test models were 3D printed and installed in a Low Speed Wind Tunnel test section and drag coefficients of the test models were measured at constant Reynolds number (Re) of 178,000 with reference areas of 0.00328 m^2 for Cases A and B. The drag coefficient of different fairing configurations are shown in Table 7. It is observed that Case A has the lowest drag coefficient of 0.356 which is lower than Case B, by 0.003.

In conclusion, it was noted that, for the results obtained in the current case study, drag coefficient results from both numerical and experimental results exhibited similar trends, i.e. Case A was more 'aerodynamic' compared to Case B. It was also noted that there was a 38–39% difference between experimental results and numerical results.

Table 7. Drag coefficient – experimental results.

Case	Drag coefficient
A	0.356
B	0.359

Reflections and discussion

At the beginning of this paper, the following research question was posed.

To what extent can C-D-I-O be successfully implemented in postgraduate research within the context of engineering education?

From the investigation, the execution of the framework seems to be most suited within the overarching research methodology. It is recommended that C-D-I-O forms the macro-level milestones within a research methodology due to its generic nature, where all investigations, whether quantitative, qualitative or otherwise, would always start with conceiving the idea, developing the overall design (e.g. research design – not necessarily an electronic drawing!), developing the design tools or products (i.e. implement) and finally executing the design (i.e. operate).

It should be noted that for this particular case study, the implementation of C-D-I-O within the project was accomplished as a pilot with a single student's project. As it has shown some success, we are now in the midst of extending it to the entire programme. Feedback from the student whose project involved the framework provided the following (taken verbatim).

Here is my perspective on the application of C-D-I-O towards the research methodology of the research project. Separating the project into distinct C, D, I and O phases helps to build focus towards achieving the deliverables of the project in the correct order for smooth execution. It fits very well with the research project structure of crafting the problem statement, writing a proposal, collecting data, and so on.

However, in my opinion there are projects that do not map cleanly into each phase of C-D-I-O. For example, in the C-D-I-O flowchart of this project the Conceive and Design phases have more numerous and well-defined tasks compared to the Implement and Operate phases.

Of course, one can learn to map C-D-I-O to any research project, which is what was done. However, there is confusion that arises in doing so from the gap in knowledge between the source definitions of C-D-I-O and figuring out how to reconcile them with the destination (applying it to the research project), which I believe can be mitigated by *clear communication between supervisor and student as well as tighter definitions for the phases of CDIO.*

In addition to feedback from the student, one member of the supervisory committee (who is also an author in the present investigation) provided the following feedback from his perspective (as a faculty member) – taken verbatim.

I took note of the impact of C-D-I-O framework on the research approach of the postgraduate student studied under the aforementioned master program. Conceive and design are the two crucial phases of any project and may adversely impact the success if an engineer struggles with them. The student was able to effectively conceive various past designs that were available for HPVs and compare according to the attributes such as the drag coefficient, sustainability and economic impact. Thereafter, he started with a rough design which was refined step-by-step considering the main components, forms and functions. The C-D-I-O approach empowered him to follow a systematic tactic in the design of the elements and consider the way they interact with each other. The design was successfully tested using numerical software, also experimentally in wind tunnel. The beauty of the C-D-I-O approach was its flexibility across different education levels from undergraduate to a master program. This student had practiced and experienced C-D-I-O during his undergraduate studies through project-based learning from semester one to semester eight. Therefore, I personally found him quite advanced in practicing the C-D-I-O concepts to the new project in masters level regardless of the depth and breadth that was expected from him.

Based on the information provided above, it may be concluded that the framework has some success in being applicable to a research-based postgraduate programme, as it is generic enough to be used for a variety of disciplines and/or projects. It should be noted that more studies are required to further validate whether the framework can indeed be successful in the postgraduate context and hence build upon the work presented in the current investigation. The conceive part of the framework consists of idea generation and a wealth of brainstorming techniques may be employed to ensure the conceive stage is performed meaningfully. Similarly, with the D-I-O stages, each stage is generic enough and allows for flexibility to apply more specific initiatives that would enable a student to achieve his or her research objectives thereby making it sensible for the framework to be applied across differing disciplines and education levels.

It should, however, be noted that as identified by the student feedback provided above, clear communication and direction would need to be provided by the supervisor of the project to the student. This is to ensure that the student utilises the framework in a manner which sets them up for success. The student would require this to ensure greater understanding of the framework, which is powerful in promoting a systems thinking approach in developing solutions to a specific challenge.

Summary

This paper provides insight into how the C-D-I-O framework may be used or embedded within postgraduate education to enhance the overall learning experience of postgraduate students. The authors conclude that the framework serves itself best when incorporated into the overarching research methodology of a research-based postgraduate research project. The authors also note that the generalising aspect of the framework lends itself nicely to being applied across discipline boundaries and based on the feedback provided by students and past investigations; there is a positive impact on the overall student learning experience.

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