Athens Journal of Technology & Engineering

Quarterly Academic Periodical, Volume 10, Issue 2, June 2023
URL: https://www.athensjournals.gr/ajte
Email: journals@atiner.gr
e-ISSN: 2241-8237 DOI: 10.30958/ajte

Athens Journal of Technology & Engineering

Published by the Athens Institute for Education and Research (ATINER)

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The Athens Journal of Technology & Engineering
ISSN NUMBER: 2241-8237- DOI: 10.30958/ajte
Volume 10, Issue 2, June 2023
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The current issue is the second of the tenth volume of the *Athens Journal of Technology & Engineering (AJTE),* published by the Engineering & Architecture Division of ATINER.

Gregory T. Papanikos, President, ATINER.

Athens Institute for Education and Research
A World Association of Academics and Researchers

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19-22 June 2023, Athens, Greece

The Civil Engineering Unit of ATINER is organizing its **13th Annual International Conference on Civil Engineering, 19-23 June 2023, Athens, Greece** sponsored by the Athens Journal of Technology & Engineering. The aim of the conference is to bring together academics and researchers of all areas of Civil Engineering other related areas. You may participate as stream leader, presenter of one paper, chair of a session or observer. Please submit a proposal using the form available (https://www.atiner.gr/2023/FORM-CIV.doc).

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Important Dates

- Abstract Submission: **deadline closed**
- Acceptance of Abstract: 4 Weeks after Submission
- Submission of Paper: **22 May 2023**

Social and Educational Program

The Social Program Emphasizes the Educational Aspect of the Academic Meetings of Atiner.

- Greek Night Entertainment (This is the official dinner of the conference)
- Athens Sightseeing: Old and New-An Educational Urban Walk
- Social Dinner
- Mycenae Visit
- Exploration of the Aegean Islands
- Delphi Visit
- Ancient Corinth and Cape Sounion

Conference Fees

Conference fees vary from 400€ to 2000€
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Athens Institute for Education and Research
A World Association of Academics and Researchers

11th Annual International Conference on Industrial, Systems and Design Engineering, 19-22 June 2023, Athens, Greece

The Industrial Engineering Unit of ATINER will hold its **11th Annual International Conference on Industrial, Systems and Design Engineering, 19-23 June 2023, Athens, Greece** sponsored by the Athens Journal of Technology & Engineering.The aim of the conference is to bring together academics, researchers and professionals in areas of Industrial, Systems, Design Engineering and related subjects. You may participate as stream leader, presenter of one paper, chair of a session or observer. Please submit a proposal using the form available (https://www.atiner.gr/2023/FORM-IND.doc).

Important Dates

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- Acceptance of Abstract: 4 Weeks after Submission
- Submission of Paper: **22 May 2023**

Academic Member Responsible for the Conference

- **Dr. Theodore Trafalis**, Director, Engineering & Architecture Division, ATINER, Professor of Industrial & Systems Engineering and Director, Optimization & Intelligent Systems Laboratory, The University of Oklahoma, USA.

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An Experiential Engineering Learning Model for Knowledge and State of Flow Creation

By Riadh Habash *

Education in professional degree programs is charged with serious responsibilities in the classroom and practice spaces. To meet these responsibilities, educators must serve as both teachers and learners in both spaces. This article demonstrates an experiential project-based learning model to enhance the teaching of an undergraduate engineering course on mechatronics. An important aspect of this model is an experiential learning model that complements the well-known international CDIO™ Initiative which is an innovative educational framework for producing the next generation of engineers. This model reflects on challenges of experiential learning for group-based design projects and faculty competition teams where learners including faculty and students collaborate to create their community of design and practice to physically and virtually share knowledge, perspectives, and opinions. The model reveals the impact of collaboration, practice spaces and exhibitions, and open educational resources in the enhancement of engineering education. The experience of adopting the model for several years recommends a number of practical approaches instructors may embrace to enable knowledge creation and enhance the effect of flow experience.

Keywords: *experiential learning, knowledge creation, reflective practice, state of flow, community of design and practice, open educational resource*

Introduction

An understanding of the new realities of globalization, cultural change, and digitization requires three converging mindsets of Age 5.0 (industry, society, and education) that help to "learn-think-research-create-change" as conceptualized in Figure 1. The ultimate "change" defines that future institutions of higher education must adapt along with the populations they serve to remain competitive and ready to account for their decisions to a wide range of stakeholders (Habash 2022). The process requires an active transdisciplinary education to integrate tools, techniques, and approaches as well as a concurrent collaboration by sharing ideas between and across disciplines, and beyond (Habash et al. 2022).

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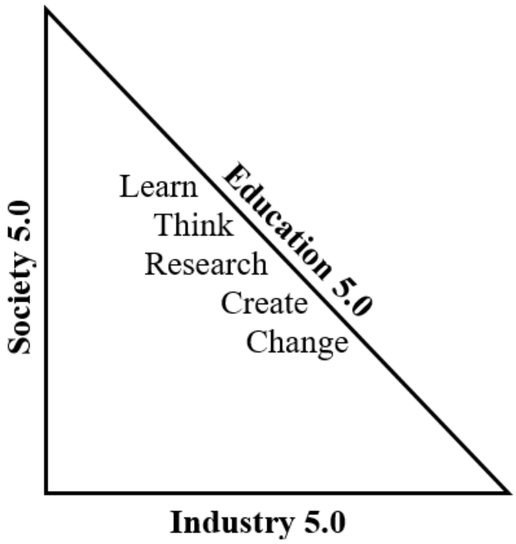
Figure 1. *Converging Mindsets of Age 5.0*



In today's engineering education, students do not learn just by sitting in classes listening to teachers, memorizing information, and preparing answers. They should think about what they are learning, write about it, reflect on their experiences, and apply it to what they feel is important (Daud et al. 2008). These experiences may take place within or outside of the classroom. The students should be active participants in the learning process, not passive witnesses to it. They should make what they learn a part of themselves. To accomplish this, the teaching content being pursued must be essentially relevant to the learner. The objective is to advance students beyond plain memorization of facts to higher-order domains of integration and applications. Such learning may happen in every domain but is perhaps most noticeable with engineering education.

Attempts to improve engineering education and student learning include a diversity of advanced pedagogical approaches. This may include first-year design courses, transdisciplinary teaching, design and practice spaces (physical and virtual), and online learning. These approaches inspire reflection and action in the form of knowledge creation and transferable skills through experiences, academically known as experiential learning. It is more specifically defined as "learning through reflection on doing", which in turn implies a constructive, reflective approach based on the "experience-share-process-generalize-apply" cycle (Younghui 2010, Gadola and Chindamo 2017, Voehl 2018). In this process, the learner takes ownership of learning, tackles risks and failure, reflects and learns from mistakes, and maybe incorporates some sort of creativity and innovation.

Experiential learning is an old concept where the contributions of Socrates, Plato, and Aristotle to its philosophies are well documented (Wurdinger 2005). Socrates' greatest contribution to experiential learning was his elenctic method. Plato calls the Socratic method elenchus, meaning, positively, a way of asking questions that help the interlocutor know what they know and do not know. In this regard, the practiced teacher only facilitates learning, accurately considering where the student is, and stimulating the student's discovery.

According to the Association for Experiential Education, experiential learning can be defined as the "challenge and experience followed by reflection and application leading to learning and growth." This definition is based on Kolb learning circle (Kolb 1984), which is formed on the background of the research from many recognized theorists in cognitive science. According to Kolb, this type of learning is defined as the process whereby knowledge is created through the transformation of experiences.

Although experience may be the basis of learning, it does not necessarily lead to it (Boud et al. 1993). Using an active learning environment can enhance the integration of theory and practice in the classroom by using instructional activities involving learning by doing (LBD) and thinking about the process. Active learning is a student-centered pedagogy in which learning activities are used to motivate and engage the students in the learning process beyond listening and passive note- taking. It promotes skill development through activities that may include system and design thinking in an active learning environment. Its main desire is to place the responsibility of learning in the hands of the learners themselves and allocates the role of leadership and facilitation to the teacher. This active learning environment should stimulate students' interest in the subject and increase their engagement and enjoyment.

Experiential education is broader than experiential learning. It is a teaching philosophy with a transdisciplinary approach toward learning. It first immerses learners in an experience and then encourages reflection about the experience to develop new knowledge and interpersonal skills, new attitudes, or new ways of thinking (Lewis and Williams 1994). Experiential education is also built upon a foundation of transdisciplinary and constructivist learning. The experiential methodology does not treat each subject as being walled off in its room but creates an interdisciplinary learning experience that mimics real-world learning. In experiential learning, there must be a mixture of content and process with a balance between the experiential activities and the underlying content or theory. Students should be able to reflect on their learning, bringing "the theory to life" and gaining insight into themselves and their interactions with the world (Voehl 2018). This holistic endeavor of learning that involves thinking, feeling, developing, and reflecting is the process of knowledge creation, not knowledge acquisition only.

Engineering students are educated into a profession where they use high-level theoretical knowledge in qualified solving of complex engineering problems. Accordingly, experiential learning focuses on the practical usage of knowledge and skills in real-world experiences to further increase learners' knowledge and develop competence in skills and behaviors. It provides opportunities for those students to interact directly with the knowledge by using tools, data collection, models, and laws of science. Such experience meets several goals including mastery of subject matter, developing scientific reasoning, and building practical skills.

Experiential education in an engineering setting is realized when learners are enthusiastically involved in activities or experiences including the design, analysis, and improvement of complex systems. These are participative, either by making or doing, which take diverse forms. Students would learn through doing and reflecting on those activities by applying in-depth knowledge to practical experience to develop skills or new ways of thinking (Habash 2019a). Experiential learning in project-based learning (PBL) goes through the application of science and engineering to open-ended problems rather than through the solution of traditionally closed exercises, to inspire creativity and innovation (Siddique et al. 2010) by integration of education and research.

This article is framed around five subsequent research questions. First, what is the gain of integrating the practical experience into a course mostly organized around the modality of classroom learning? Second, what is the role of group-based student projects, competition teams, a community of design and practice (CODAP), and physical and virtual exhibitions in experiential learning? The third question is what collaboration, exhibition, judgment, and sustainability mean to experiential learning. The fourth question is if various course components impact students' experience of knowledge creation. The fifth question is about how can teachers encourage flow and how can students achieve flow. To realize the above questions, an enhanced experiential learning model that complements the well-known international CDIO™ Initiative is proposed, implemented, and assessed for several years. This active learning strategy is supported by an open educational resource (OER: g9toengineering.com) developed by the instructor (author) to enable knowledge creation and enhance the effect of the flow experience.

The C-CDIO-R-J-E Experiential Model

Experiential learning is not new but an age-old concept. In Greece, knowledge was classified into four categories: know what; know why; know-how; and know who. "Know what" is related to facts, is close to the information, and is related to typical engineering education. "Know why" represents principles and laws. "Know- how" is related to transferable skills and the ability to do or build something. "Know who" refers to information about who knows and who knows what to do. This knowledge is related to engineers knowing who they can consult when they encounter a problem (OECD 2000).

Aristotle wrote in Nicomachean Ethics that "the things we have to learn before we do them, we learn by doing them", as a principle for thousands of years, is often overlooked in the domain of typical education. Adjusting education to a such activity means adopting an open curriculum that provides learning from experiences resulting directly from one's actions, as compared with learning from watching or listening (Habash 2019a).

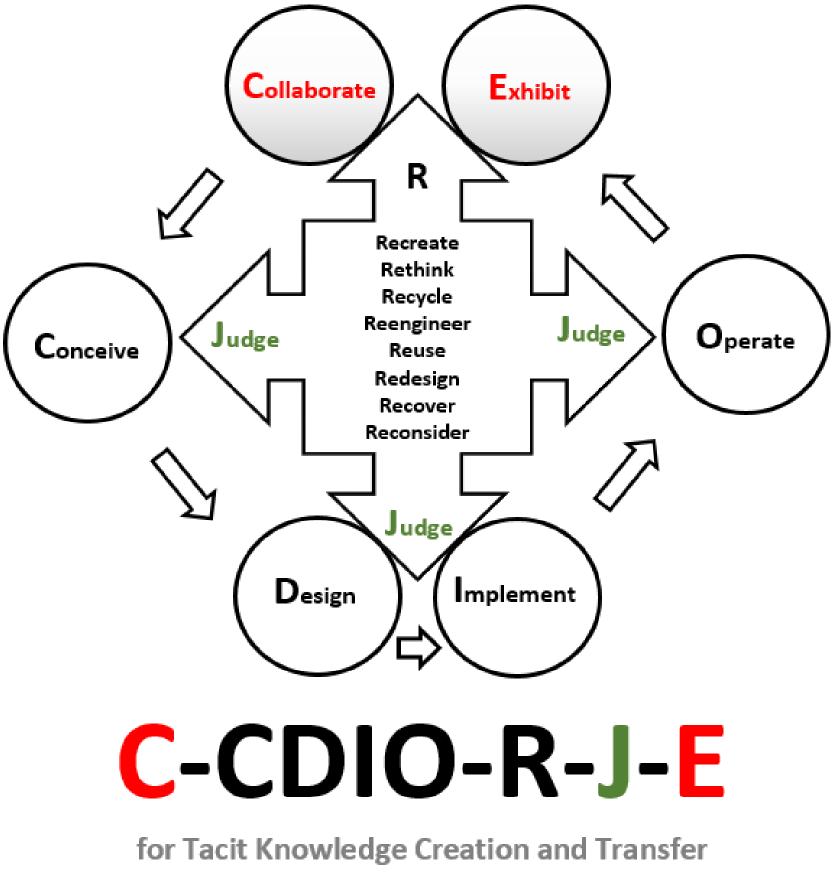
By moving beyond theory to the realm of LBD design, the learner gets a first-hand experience of practicing what has been taught in terms of fundamental concepts on which a system is based. This plays a crucial role in retaining concepts and ideas. The principle has been promoted widely and in many forms, including trial-and-error learning or discovery versus instruction, practical experience versus book learning, and others (Lester and Kezar 2017). LBD has long been a tradition in the technology disciplines including engineering. However, there is no doubt that it is the "hands-on" work that reinforces theory into practice through the sharing of knowledge between individuals as typically occurs through joint activities in combination with physical proximity. Such experiential activity should include exploration, sharing, processing, and application. This requires the student to perform an activity or task, share the results and observe, discuss, and then reflect on the process, connecting it with real-world examples and applying it to another situation.

Engineering as the art of shaping and navigating the design promotes the "invisible" learning that aligns with knowledge creation. An essential building block of this methodology is experiential learning which goes beyond LBD by stressing the need to educate students to understand how to conceive-design-implement- operate (CDIO) complex value-added engineering systems in a modern, team-based environment. The CDIO teaching approach changes the way students learn and how teachers teach (Wang et al. 2021). CDIO collaborators have adopted this approach as the framework of their curricular planning and outcome-based assessment through ways that may together be depicted as active learning.

Adding to the CDIO framework is the role of collaboration "C", judgment "J", exhibition "E", and R's of sustainability "R". This is reflected in developing the experiential C-CDIO-R-J-E model shown in Figure 2. The model complements the well-known international CDIO™ Initiative which is an innovative educational framework for producing the next generation of engineers. Collaboration and connection establishment (including online) provide a platform for knowledge transfer through a process of "socially constructed learning". This is based on the idea that the social nature of collaborative student groups offers the opportunity to learn through shared conversations among participants and exposure to new ideas. The realization of ethics and judgment consists of taking the most appropriate decision in the face of a dilemma in which one must choose the one that is most in line with professional accountability. On the other hand, an exhibition by seeing design and hands-on work is a strategy that calls for making students' work visible to transfer the knowledge embedded in how work is done. The model is inspired by sustainability (Rs: recreate, rethink, recycle, etc.) to direct student thoughts about the environment in which we work and live (Habash 2017).

The proposed C-CDIO-R-J-E experiential model presents the "how" of the knowledge transfer, the practice that translates a learning institution's vision into an innovative exercise. This approach makes the students sense that their teacher is enthusiastic about teaching and confident in their learning where classes are open to diverse experiences and the teacher continues as a creative mediator by facilitating critique, encouraging partnership in learning, and fostering reflective practice. This model would suit any course in which practice is pertinent.

Figure 2. *The Proposed Experiential C-CDIO-R-J-E Model*



Setting of the Course

In engineering, mechatronics is a discipline that reflects transdisciplinary real-life applications effectively. It is the synergic design of computer-controlled systems that integrates mechanical, electrical, and computer tools with information systems for the manufacture of products and processes. Such integration offers a wider spectrum of assignment potential and thereby also opportunities for student freedom in being creative (Habash and Suurtamm 2010). In promoting an active and collecting environment for student participation in the learning process, the instructor sets a learning atmosphere for everybody, including the teacher (Habash et al. 2011).

Initially, the teaching experience under consideration has specifically evolved from PBL to the proposed C-CDIO-R-J-E experiential model. It is shown that projects are used as an integral and essential part of the learning activities provided in teaching mechatronics especially when they are made part of a larger engaging learning task like faculty competition initiatives. Group-based design projects with sustainability in mind have been implemented in teaching a course on mechatronics to third-year mechanical engineering students. The average class size is 150 students. Teaching this course is based on both teacher- centered and learner- centered environments. The knowledge structure approach is a steady move from direct instruction in the form of lectures and tutorials, to hands-on lab tasks, to self-controlled experiences of 10-weak design projects. The projects are introduced at the beginning of the semester through formal request-for-proposal announcements. Each group of two-three students is expected to select one project idea to proceed with throughout the semester. A proposal must be prepared by each group in the fifth week, which concludes the conceptual design phase. Upon approval, the group proceeds toward detailed design and prototyping. These projects aim to embed learning in real-world contexts, which give students a sense of responsibility and ownership.

The projects are rewarding, as they often afford the students their first opportunity as design beginners. These projects require knowledge of electronics, mechanics, and simulation as well as the acquisition of components such as breadboards, sensors, motors, gears, controllers, and other accessories. Such a PBL experience needs careful design and continuous monitoring by the instructor. Many of the group-based projects share a systematic reverse engineering approach for analyzing the design of existing devices in system prototypes used for major student competition teams. Such projects are scientifically sound and relatively open-ended where the students apply a typical iterative design process, run tests, and diagnostic troubleshoot on all performance parameters. They require in-depth knowledge and information about economics and project management, standards and codes with appropriate attention to health and safety risks. However, they involve occasionally encountered issues.

The course concludes with an exhibition of project prototypes where students share the experience as well as with students from other classes and sometimes visitors from local high schools. This represents a collaborative exercise that involves reflection on the subject matter from the viewpoints of different people and disciplines. The goal of this exhibition is to increase awareness about engineering design in general and the faculty competition teams in particular. Another key deliverable is an educational video, which should stand as a design communication for the project. Several videos are selected to be shared at the course OER.

Student competition initiatives seem to play on a different level, at least in engineering education. They are renowned international, long-term events rather than classroom activities, and they offer all the elements that are the key to successful experiential learning. They are open-ended tasks where reflection is facilitated through subjective experience, objective results, advice, and judgment from industry experts. In this regard, several groups of students from the class pick up design projects related to major competition initiatives funded by the faculty's Brunsfield Centre for Engineering Student Projects and Entrepreneurship. This participation in inter-university competitive teams such as Supermileage, SAE Formula Electric, Baja, SAE Aerospace, Rocketry, Roboboat, and Rover (Figure 3) is critical for the advancement and success of the teams in diverse national and international thoroughly judged competitions. Teams work on multiple aspects of their projects, from mechanical, electrical, and software. They usually develop and test various mechatronic systems including engines, avionics, ignition mechanisms, and different controls. The Faculty's John McEntyre Team Space provides a collaborative space for the pre-competitive teams as well as the infrastructure required to push technological boundaries, promote the development of skills and expertise, and strive for success. In general, the course represents a recruitment hub for the faculty competition teams.

Figure 3. *Examples from Student Competition Teams*

State of Flow Experience

According to positive psychologist Csikszentmihalyi (1982), flow is a state of mind in which a person becomes fully immersed in an activity. It is a learning journey from routine and unfeeling to enlightenment, empowerment, emancipation, and an entrepreneurial mindset. Matching challenge and skill could be an important consideration in this state. It is often associated with rewarding creative arts, however, it may also occur while engaging in a sport, dance (Cherry 2022), or technology. The state of flow can be attained by balancing the skills students possess with the challenges.

Students learn in many ways, so the challenge for teachers is to discover which approaches help students to learn most effectively. Both flow and experiential learning underline the importance of the learning environment and the choice of task. The advantages of flow experience are obvious, as it improves students' ability and their attitude to learning (Kiili 2005). Experiential learning provides an intentional way of shaping hands-on learning and may have consequences for learner engagement (Younghui 2010).

The above state may be summarized as LBD and emphasizes that the material and approach used during the learning process are critical for deep engagement in the task (Gauntlett 2007), hence for entering the state of flow. As a way to realize this state, the CDIO methodology has been adopted by the author in teaching several undergraduate courses including the course under consideration.

Often, groups of students try to build a particular system for a competition team with a tendency of getting fascinated with details. They spend extra hours added to their class experimenting in a mind-absent flow and are driven by the needlessly ambitious plan for a fully sophisticated system but fail to implement their plan with the available resources or time. During the consultation with the instructor, the students explore their inclination to over-engineer the system and change their minds toward a much simpler solution to complete the work.

Experiencing flow during the learning process is supposed to be linked to improved learning outcomes (Shernoff et al. 2003). By combining all course learning components, it is observed that active experiential learning is a supportive form to enter the state of flow but it is not enough requirement. To deepen flow and maximize student concentration, the top course projects and winning competition teams are usually awarded bonus marks in addition to the full graded marks. In general, the final course grades are largely a reflection of the effectiveness of the C-CDIO-R-J-E experiential teaching model.

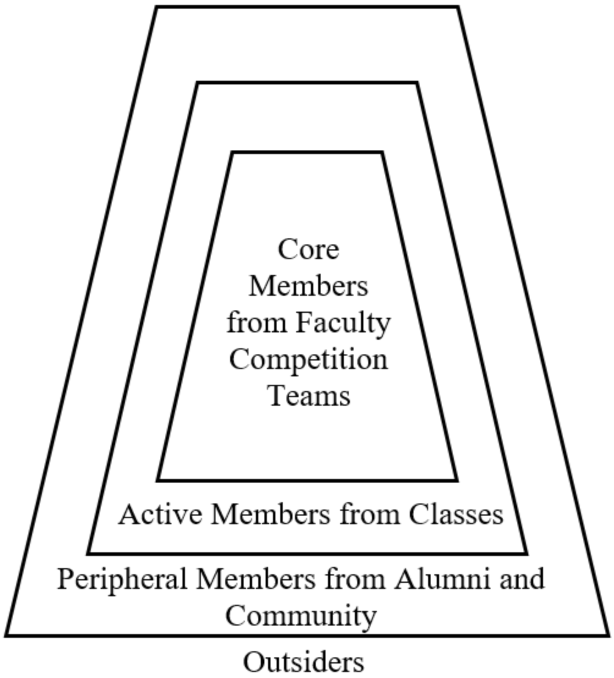
Community of Design and Practice (CODAP)

The engagement of students in course projects and faculty team competitions tends to naturally conform to the criteria laid out in Kolb and Kolb (2005); in particular, their suggestion that experiential activities draw students into a community of practice. The practice means students employ what they learn in the classroom. Therefore, this course plays a significant role in creating new competition teams and feeding the existing teams with members, ideas, and solutions for continuation and progress. This means expanding their knowledge beyond the classroom and getting a practical hands-on experience that all employers want.

Communities of practice were common as far back as ancient times. In Greece, for instance, corporations of metalworkers, potters, masons, and other craftsmen had both a social purpose and a business function (members trained apprentices and spread innovations). In the Middle Ages, guilds played similar roles for artisans throughout Europe. Today's such communities are different in one important respect: instead of being composed primarily of people working on their own, they often exist within large organizations (Al-ghamdia and Al-ghamdib 2015, Habash 2020).

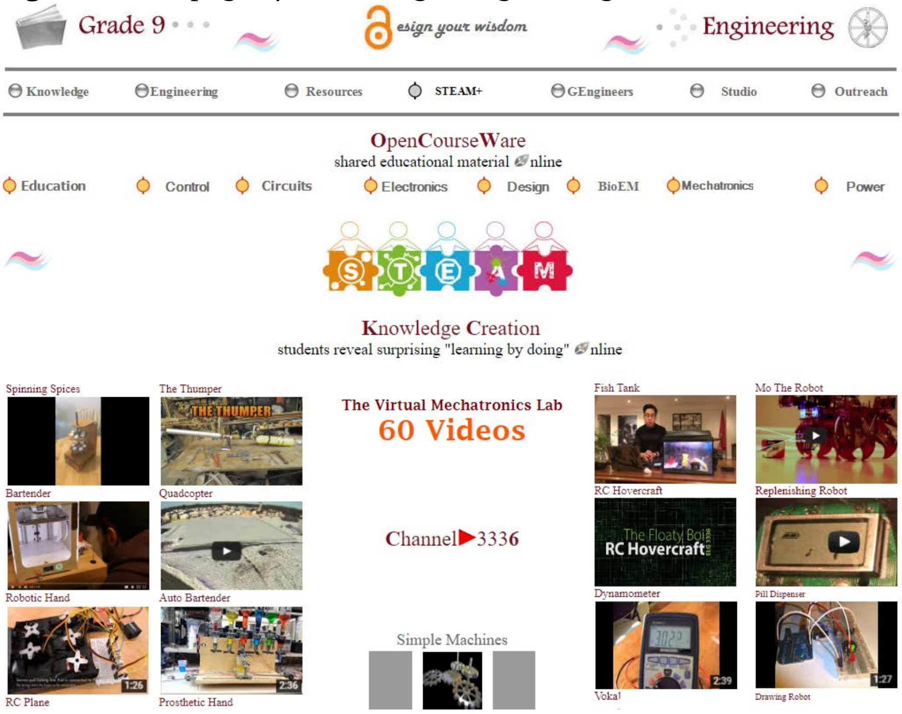
A CODAP may be regarded as a layered structure of participants, frameworks, ideas, physical and virtual spaces as shown in Figure 4. It is a mechanism to facilitate social interactions, knowledge creation, and sharing within a culture of collective learning. Over years, graduates from the faculty joined graduate programs, the industry, and other institutions. Several others established their firms and continued collaborating with the faculty. Today, those graduates represent an outer community that supports and benefits from the CODAP. It has been the author's experience that the CODAP can benefit students and the community through positive social interaction networking that enhances belonging and experiential engineering learning.

Figure 4. *A Framework for a Community of Design and Practice*



With the emergence of Web 2.0, many techniques that allowed the considerable potential for developing CODAP roles in learning processes have become available, which has, in turn, led to the emergence of the virtual CODAP (VCODAP) (Vinson 2013, Habash et al. 2022). The Internet is currently one of the first digital places where people go for information and knowledge, and it can be of great assistance to both educators and students. To realize this fact, an OER, namely "g9toengineering. com (Figure 5)" as a VCODAP was developed by the author in 2007 to support teaching and to provide open space for knowledge in various disciplines and topics (Habash 2019b). This OER provides in addition to multiple resources, a list of student projects in the form of educational videos as well as the activities of various faculty competition teams.

Figure 5. *Frontpage of the OER: g9toengineering.com*



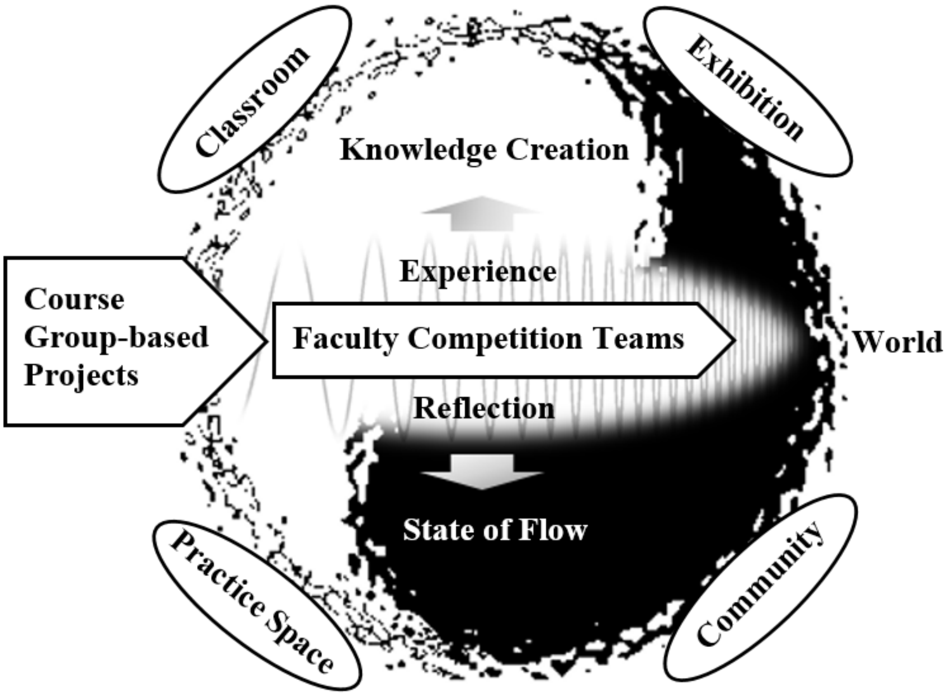
Reflective Practice and Knowledge Creation

Reflective learning facilitates learners to activate prior knowledge and develop new knowledge. In reflective practice, students engage in an endless cycle of self-observation and self-evaluation to realize their actions and the reactions they induce in themselves and other learners. The CODAP concept applies very well to the structure of teaching the course under consideration in terms of classroom, design and practice spaces, exhibition, community outreach, group-based projects, and faculty competition initiatives. The reflective practice of the group-based projects feeding the competition teams takes a constructivist approach to knowledge creation and sharing as shown in Figure 6.

To effectively realize reflective practice, certain adjustments in the education system should take place where classes will be more open spaces for diverse learning experiences and teachers will continue as mentors, guides, facilitators, designers, and organizers of learning tools. However, this break with traditional sequences is not without debate. Students may be unenthusiastic to depart their comfort zone if they do not see the value of learning strategies that require more effort. To this end, there is no specific answer to that dilemma, no recommendation for how the components of a learning environment should be gathered for the highest benefit of learning.

Reorienting learning away from knowledge acquisition toward knowledge creation and translation involves careful consideration of the students as learners. Knowledge is created due to two distinct learning processes: grasping and transforming of experience (Kolb 1984). Grasping may be hypothesized as a scale between concrete experience and abstract conceptualization. Transforming spans from active experimentation to reflective observation (Jentsch et al. 2012). Because the final verdict on the effectiveness of an approach lies in learning outcomes. The focus should center on the student experience and reflection supported by facilitating interaction in practice and exhibition spaces as well as OERs.

Figure 6. *Reflective Practice within the Framework of CODAP*



Assessment and Feedback

To improve the quality of teaching methods and practices, there are several strong approaches to the assessment of pedagogical innovations and student performance in engineering education. These include in addition to institutional self-evaluation, student online anonymous surveys and feedback comments as well as instructor observation, critique, and judgment.

When brainstorming for the online anonymous survey, the instructor thought of four specific questions about the effectiveness of the course learning components including lectures, design modules, lab tasks, and projects. Students' satisfaction concerning the course learning components and results are measured by analyzing the data collected from Questions 1 to 5 (Table 1). In general terms, the data from Question 1 of the survey shows that the majority of students support learner- centered learning (case studies and projects) over teacher-based learning (lectures). In particular, only 27% of the students showed interest in competition teams since only about 30% of the students participate in these teams. Students' feedback from Questions 2 and 3, shows the impact of the C-CDIO-R-J-E experiential model on the learning process. Data from Question 4 indicates that about 71% of students "agreed" with the CODAP and OER creation. Data from Question 5 shows that a good number of students engaged and enjoyed the course activities and entered the state of flow.

Despite the satisfaction, this process might sometimes involve student discomfort by taking responsibility for their learning. Results from Table 1 show that majority of students agree with the learning approach and usually recommend activities that reflect real-life applications. The data from group interviews show that students want and expect more LBD via PBL from other courses across the semester. Based on student comments, it is believed that educators have an opportunity to proactively drive the motivation of their students to enhance their learning and develop the graduate attributes.

Table 1. *Course Anonymous Survey Outcomes*

Survey Questions	**Student Response**			
Q1: I learned for future practice from the course content overall, however, I gained more knowledge and experience from	Lectures/ Tutorials 51%	Design Modules 57%	Project 83%	Competition Teams 27%
Q2: While working on the project, I learned more about	Design 76%	Hands-on 82%	Testing 79%	Planning 71%
Q3: These three activities were practiced in the course, However, I benefited the most from	Collaborati on 78%	Judgment 56%	Exhibition 89%	Sustainability 73%
Q4: I think CODAPs including OERs improve understanding of the subject content	Strongly Agree 61%	Agree 20%	Disagree 9%	No idea 10%
Q5: I was totally involved in what I am doing in the course. I have experienced it. With what and how often?	Mostly with Project 34%	Mostly with Design Modules 19%	Sometimes 24%	No idea 23%

Feedback comments on students' performances are critical because they assist in knowing the strengths and limitations of the course in general. Students' feedback indicates notable enthusiasm towards the course on mechatronics, despite its demanding workload. The collected student feedback and data clearly show that unleashing engaging activities into web-enhanced/hybrid/blended paradigms where students receive traditional and technology-mediated learning may significantly improve student analytical thinking, reflective judgment, and self-efficacy (Habash 2018). Feedback can pinpoint the limitations associated with students' intangible understanding related to each of the instructional goals. A significant element of assessment and reflection is student satisfaction, which is related to but different from success as evidenced by student feedback comments and perceptions about the experience in which the learning outcomes meet most of their needs. The most notable quotations during the online survey are the following.

> "The project is interesting, it involves grasping knowledge learned in the classroom and applying it on a large scale in real-life application."
> "Interesting to learn about real-life situations."
> "Real-life implementations. Teamwork is the key. Punctuality is important. I believe this will add to my experience in the future. Improvements are always possible but can't think of any right now."
> "It is certainly useful and is unique. Many things in this world are educated guesses."
> "I believe the development of student projects has a large impact on the learning objectives of students. While working on this project, I learned much more about my topic and was able to condense it in a way my peers could understand. It informally improved my design thinking and hands-on skills. The OER allowed me to connect with the audience in a relaxed manner."
> "Personally, building the project was the best aspect of the course as it allowed me to showcase my creative skills and combine them in a way to educate others on a topic I am very interested in."

Based on the student comment, it is believed that teachers have an opportunity to proactively drive the motivation of their students to impact their perspective on learning. Students appreciated the project and competition task experiences and thought they were efficient in promoting collaboration, systems thinking, and design thinking.

Discussion and Conclusion

Engineers educated today will become industry leaders, educators, and researchers of the future. They should be well equipped to tackle and conquer the rising challenges. To be effective in preparing for these progressively difficult roles, the education system must be far more creative and aspiring intellectually. Teaching content should not be used as an end in itself, but as a means of helping students learn how to learn. Teaching should shift from covering all required content to guiding principles of the learning process. Grading should not be based on reciting back lecture notes. Sometimes, grading is very degrading for students.

Returning to the research questions after collecting data from observation, survey, feedback comments, and interviews. The first question asked about the gain of integrating practical experience into the course. The data confirms a significant advantage in this regard. The second question was about the impact of group-based student projects, faculty competition initiatives, CODAP, and physical and virtual exhibitions in experiential learning. The effect is evident on student engagement and learning. The third question asked about the meaning of collaboration, exhibition, judgment, and sustainability in experiential learning.

Data shows that these activities complement the CDIO Initiative and have a great influence on experiential learning. The fourth question is if various course components impact students' ability to create knowledge. It is evident from students' performance by connecting new knowledge with knowledge and concepts that they already gained in the course, thereby constructing new meanings. The fifth question was about students' involvement in the course activities. A good number of students engaged and enjoyed the course activities and entered the state of flow.

Implementing the proposed C-CDIO-R-J-E experiential model including the CODAP requires a change that might be time-consuming and a little bit expensive, but collaboration amongst students, faculty, university and industry facilitates the ground for lessening the task. Not only does this model serve the students in learning competencies but in creating and sharing resources such as equipment and software applications. As observed from several years experience of teaching the course, the integration of group-based experiential learning with CODAP enhances the interprofessional skills of students more than just solving pre-determined theoretical exercises. Students' feedback indicates notable enthusiasm towards the course, despite its heavy workload. Based on students' feedback, the course can address major graduate attributes that are expected from any engineering institution.

The results of this research have identified several critical issues when teachers and students try to take advantage of the proposed C-CDIO-R-J-E experiential model and CODAP as a space of collaboration and source of information for knowledge creation and innovation. Such a combination is an effective indicator of informal learning. It evolves to address normally shared interests and problems. It might postulate a viable alternative to the learning programs being offered by recognized academic institutions. This will place a burden on universities to offer more accommodating practices for the recognition of informal learning and to hold on to their existing domination of educational credential recognition.

This teaching model is helpful, not only in fostering students' practice capability, innovation realization, and team collaboration spirit but also in stimulating the learning curiosity and enthusiasm for research investigation. Therefore, it is recommended that teachers should construct the curriculum with a student-centered approach. It is crucial to make the course easy to study for all students, regardless of their learning background. The author believes that in addition to industry collaboration and research publication, the model is enriched by the ability to engage learners physically, cognitively, and socially in various projects and faculty competition initiatives. It consequently prepares future talents and enhances graduate employability.

Acknowledgments

The author would like to acknowledge the large number of students who have taken the course and participated in faculty competitions teams over the past several years for trialing this learning approach, and would especially like to thank them for their efforts and many productive suggestions.

References

Al-ghamdia HAK, Al-ghamdib AAK (2015) The role of virtual communities of practice in knowledge management using Web 2.0. In *International Conference on Communication, Management and Information Technology, Procedia Computer Science* 65: 406–411.

Boud D, Cohen R, Walker D (1993) *Introduction: understanding learning from experience*. In D Boud, R Cohen, D Walker (eds.), *Using Experience for Learning*, 1–17. Bristol, PA: Society for Research into Higher Education.

Cherry K (2022) *What is a flow state?* Available at: https://www.verywellmind.com/what-is-flow -2794768.

Csikszentmihalyi M (1982) Toward a psychology of experience. In L Wheeler (ed.), *Review of Personality and Social Psychology*, 13–35. Beverly Hills, CA: SAGE Publications.

Daud S, Abdul Rahim RE, Alimun R (2008) Knowledge creation and innovation in classroom. *World Academy of Science, Engineering and Technology International Journal of Social, Behavioral, Educational, Economic, Business and Industrial Engineering* 2(4): 440–444.

Gadola M, Chindamo D (2017) Experiential learning in engineering education: the role of student design competitions and a case study. *International Journal of Mechanical Engineering Education* 47(1): 3–22.

Gauntlett D (2007) *Creative explorations: new approaches to identities and audiences*. Oxon, NY: Routledge.

Habash R (2017) *Greening engineering by innovation, entrepreneurship, and design*. Boca Raton, FL: CRC Taylor and Francis.

Habash R (2018) Unleashing knowledge creation and sharing in a reflective open education. In *The Canadian Engineering Education Association's Annual Conference*, Vancouver, Canada, June 3-5.

Habash R (2019a) *Professional practice in engineering and computing*. Boca Raton, FL: CRC Tylor and Francis Group.

Habash R (2019b) g9toengineering: a virtual community of practice in knowledge creation. In *IEEEEduCon*, Dubai, UAE, April 9-1.

Habash R (2020) Transfer of knowledge creation in engineering design. In *Canadian Design Workshop*, Waterloo, Canada, December 7-9.

Habash R (2022) Phenomenon-based learning for age 5.0 mindsets: industry, society, and education. In *IEEEEduCon (Global Engineering Education Conference)*, Tunis, Tunisia, March 28-31.

Habash R, Suurtamm C (2010) Engaging high school and engineering students: a multifaceted outreach program based on a mechatronics platform. *IEEE Transactions on Education* 53(1): 136–143.

Habash R, Suurtamm C, Necsulescu D (2011) Mechatronics learning studio: from "play and learn" to industry-inspired green energy applications. *IEEE Transactions on Education* 45(4): 667–674.

Habash R, Hasan M, Chiasson J, Tannous M (2022) Phenomenon- and project-based learning through the lens of sustainability. *International Journal of Education* 38(1): 1–7.

Jentsch D, Riedel R, Mueller E (2012). Flow and physical objects in experiential learning for industrial engineering education. In *19th Advances in Production Management Systems (APMS)*, Sep 2012, Rhodes, Greece.

Kiili K (2005) Digital game-based learning: towards an experiential gaming model. *Internet for Higher Education* 8(1): 13–24.

Kolb DA (1984) *Experiential learning: experience as the source of learning and development*. New Jersey, NJ: Prentice-Hall.

Kolb AY, Kolb DA (2005) Learning styles and learning spaces: enhancing experiential learning in higher education. *Academy of Management Learning and Education* 4(2): 193–212.

Lester J, Kezar A (2017) Strategies and challenges for distributing leadership in communities of practice. *Journal of Leadership Studies* 10(4): 17–34.

Lewis LH, Williams CJ (1994) In Jackson L and Caffarella RS (eds.), *Experiential Learning: A New Approach*, 5–16. San Francisco, CA: Jossey-Bass.

OECD (2000) *Knowledge management in the learning society: Centre for Educational Research and Innovation Education and Skills*. Paris, France: OECD.

Shernoff DJ, Csikszentmihalyi M, Shneider B, Shernoff ES (2003) Student engagement in high school classrooms from the perspective of flow theory. *School Psychology Quarterly* 18(2): 158–176.

Siddique Z, Hardre PL, Bradshaw AC, Saha M, Mistree F (2010) Fostering innovation through experiential learning. In *Proceedings of the ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE 2010*, Montreal, Quebec, Canada, 15-18 August 2010, Paper No. DETC2010-28892.

Vinson CA (2013) *Fostering virtual communities of practice to move cancer control research into practice*. ProQuest Dissertations and Theses. The George Washington University.

Voehl F (2018) *Best practices in experiential learning*. Available at: https://www.smartsims.com/wp-content/uploads/2018/05/best-practices-in-experiential-learning.pdf.

Wang Y, Gao S, Liu Y, Fu, Y (2021) Design and implementation of project-oriented CDIO approach of instrumental analysis experiment course at Northeast Agricultural University. *Education for Chemical Engineering* 34(Jan): 47–56.

Wurdinger SD (2005) *Using experiential learning in the classroom: Practical ideas for all educators*. Lanham, MD: Scarecrow Education.

Younghui C (2010) Study of state theory and experiential learning. In *2010 Second International Conference on MultiMedia and Information Technology*.

Athens Journal of Technology and Engineering - Volume 10, Issue 2, June 2023 – Pages 107-122

Embodied Energy and Carbon Footprint of Concrete Compared to Other Construction Materials

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The main objective of infrastructure design codes is to protect the public's welfare, health, and safety, none of which appear directly related to the current sustainability movement that has focused on protecting the natural environment, conserving resources, and minimizing the toxicity of construction materials and processes. Some United States jurisdictions have adopted language related to sustainability based on the United States Green Building Council to curtail adverse effects of global climate change, minimize environmental impact of new construction of built assets (i.e., buildings and infrastructure), and in some cases, improve air quality in the community. The focus of this paper is to compare the embodied energy and carbon footprint of various construction materials: concrete, steel, timber, masonry, and fiber reinforced composites. To properly compare these materials from a sustainability standpoint, we propose an index that characterizes material ecological properties by dividing strength and stiffness by embodied energy. The index is similar to the structural specific properties index used to characterize the mechanical properties of materials (i.e., strength and stiffness divided by density). Using this ecological index, concrete and steel appear to be the most sustainable materials. As a result of their higher strength and stiffness, concrete and steel require less embodied energy to satisfy specific structural demands.

Keywords: *embodied energy, carbon footprint, LEED, specific embodied energy*

Introduction

From conventional to high-performance composite materials, construction materials have been developed and modified over the past century. With the increased use of contemporary materials, such as concrete, steel, timber, masonry, and fiber reinforced composite, steps are currently being taken to reduce their pollution impact and to promote their sustainability. Driven in part by governmental policies to increase awareness of the effects of greenhouse gases and to utilize limited natural resources more efficiently, sustainability has become an important aspect in infrastructure design. Many of the innovations in sustainability have been spearheaded by professional organizations, such as the American Society of Civil Engineers (ASCE), the American Institute of Steel Construction (AISC), the American Concrete Institute (ACI), the American Forest & Paper Association (AF & PA), the U.S. Green Building Council (USGBC), etc. These organizations' primary sustainability goals are to reduce the carbon footprint of structures, curtail

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any negative environmental effects caused by construction, improve indoor environmental quality, and assuage adverse social and economic impact.

The main approach for attaining such goals is by working with engineers and architects to implement changes that reflect sustainability methods in design and construction of built assets – buildings and infrastructure. To assess the degree of achievement, professional organizations have developed a sustainability certification for existing and new structures. Certifications rate their overall impact on the environment, society, and the economy. The USGBC leads the way via their Leadership in Energy and Environmental Design (LEED) certification program which serves to standardize the overall sustainability of buildings using a point system in LEED v4.1 (current version as of 2021).

The LEED certification program has created standards for the design and development of new construction of various types of buildings. LEED awards points based on the following eight parameters: Location and Transportation (16 points), Sustainable Sites (10 points), Water Efficiency (11 points), Energy and Atmosphere (33 points), Materials and Resources (13 points), Indoor Environmental Quality (16 points), Innovation (6 points), and Regional Priority (4 points). The standard point values are assigned to new construction but can change depending on building type. Classification is assigned as Certified (40 to 49 points), Silver (50 to 59 points), Gold (60 to 79 points), or Platinum (80 points and above).

Of the eight areas that LEED addresses, Materials and Resources as well as Innovation are directly related to sustainable materials. Indoor Environmental Quality is indirectly related to sustainable materials, as three of its 16 points assess Low-Emitting Materials. Energy and Atmosphere should also be considered in evaluating the sustainability of materials since upfront carbon emissions generated in the mining, harvesting, processing, transportation, and installation of construction materials can constitute a larger portion of a new building's embodied energy compared to all other stages in its life cycle (WGBC 2019).

Building sustainable infrastructure has been more expensive and less profitable for developers, but recent advances in materials, processes, and equipment have made the cost of building 'green' competitive. For a typical building, the structural system usually accounts for 10 to 20% of the construction costs (Kneer and Maclise 2008). The increased cost associated with achieving the lowest LEED certification is approximately 4%. Higher certification levels have increased cost premiums; for example, gold certification can cost up to 10%, while Platinum up to 12.5% (WorldBGC 2019). More importantly, the life cycle cost, including energy consumption of the building, can be lower compared to the costs of conventional construction (WorldBGC 2019).

Some of the most important changes related to sustainable construction have been spurred by government agencies through the adoption of LEED certification for public projects; for example, requiring all public governmental buildings to be LEED certified. To further increase public sector investment in the development of LEED certified structures, incentives have been offered, such as grants, tax credits, and low interest loans. Incentives for private development include higher rents, sale prices, and occupancy rates for LEED office spaces (Miller et al. 2008). Each incentive confers lower investment risks and higher profits. In fact, the potential lower life cycle cost is the primary reason many private and public entities are specifying LEED certified structures. Life cycle cost analyses support the return on investment, not just the initial cost.

Pollution Impact of Infrastructure Materials

As noted, two sustainability areas, Energy and Atmosphere as well as Indoor Environmental Quality, indirectly relate to sustainable materials. These areas are primarily concerned with control of pollutants and their effects on public health and the environment. Of particular importance is curtailing CO_2 emissions to reduce the adverse effects of climate change. Table 1 lists CO_2 emissions per ton generated in the production of various materials; the most widely used of which is concrete. Most of the embodied CO_2 in concrete comes from cement, which produces nearly as much CO_2 as the material itself. Thirty-five percent is generated by using fossil fuels during the heating of limestone and clay, while the remaining 65% is released in the calcination process when calcium carbonate ($CaCO_3$) from limestone is converted to calcium oxide (CaO):

$$CaCO_3 + \text{Heat} \rightarrow CaO + CO_2$$

It is estimated that between 33% and 57% of CO_2 produced during cement production can be reabsorbed into concrete surfaces during a 100-year product life cycle through a reverse carbonation process (Pade and Guimaraes 2007). This is usually not accounted in the total CO_2 reported.

Table 1. *Net CO_2 Emissions in Producing Various Materials*

Material	**Net CO_2 Emissions (kg CO_2/kg)** [a]
Aggregate	0.005
Framing lumber	0.033 [b]
Brick	0.25
Concrete blocks	0.29
Recycled steel (100% from scrap)	0.30
Concrete	0.95 [c]
Cement	1.0
Steel (virgin)	1.30
Glass fiber reinforced plastic (GFRP)	18.8
Carbon fiber reinforced plastic (CFRP)	35

[a]Values are from various sources (primarily form Crawford et al. 2019 and Ashby 2009) and are based on gathering and processing of raw materials, primary and secondary processing, and transportation.
[b]This value depends on where the lumber is harvested and can be as high as 0.38; Also, carbon stored within wood will eventually be emitted back to the atmosphere at the end of the useful life of the wood product. Near-term net CO_2 emissions, including CO_2 storage within material, can be considered negative, – 0.46 kg CO_2/kg).
[c]This value is estimated by the Portland Cement Association estimates; also see Figure 1.

Global cement production contributes approximately eight percent of total CO_2 produced each year. However, it is difficult to establish a definitive value since different countries report different figures. Even in the United States, the Environmental Protection Agency (EPA) reports that different states, in some cases, fabrication plants, report different values (U.S. EPA 2009). This is expected given that equipment, local regulations, and methodology used to quantify CO_2 emissions differ from plant to plant. Therefore, any reported values should be used only as average estimates.

Though only approximately 25% of a building's environmental impact is attributed to its materials (WGBC 2019), this total environmental impact happens immediately, while the environmental impact of operations occurs over the life of buildings. Therefore, considering the conclusions of the Intergovernmental Panel on Climate Change report (IPCC 2018) regarding the catastrophic changes to the environment if drastic steps are not taken immediately to reduce CO_2 levels in the atmosphere, the initial global warming effect from materials should be expected to be much more severe than those from operations.

Current laws have incentivized limiting the amount of pollution produced in the manufacturing of infrastructure construction materials. Companies producing these materials have opted to reduce energy consumption and recycle to comply with current environmental protection laws and decrease processing costs. Limitations of air emissions and waste from manufacturing have both contributed to environmental improvements in these industries.

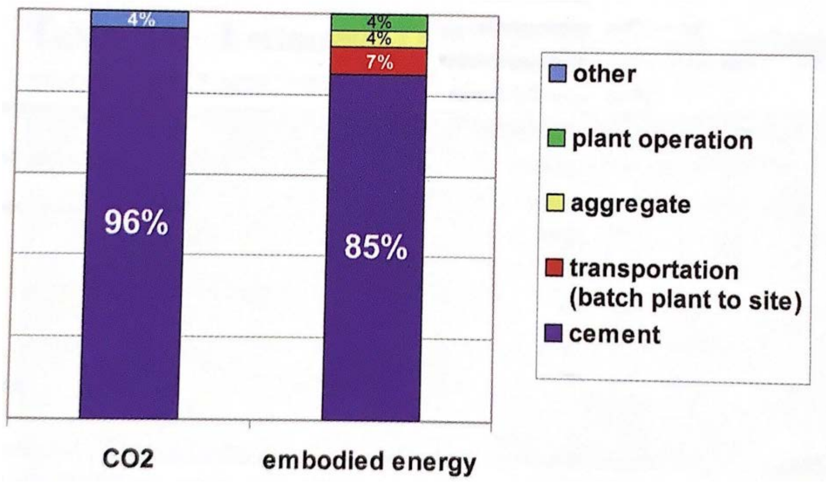
Another way in which infrastructure construction has impacted the environment is through building demolition, with solid waste from demolition increasing approximately 20% from 1996 to 2003 (U.S. EPA 2009). The average percentage breakdown of solid waste by materials is as follows: 40 – 50% concrete and mixed rubble, 20 – 30% wood, 5 – 15% drywall, 1 – 10% asphalt roofing, 1 – 5% metals, 1 – 5% bricks, and 1 – 5% plastics (U.S. EPA 2009). As resources that go into the built environment become scarce, it is anticipated that most of these materials will be reused or recycled. In some cases, existing buildings can be reused, either the entire building or parts of it. These options should be considered in every project to decrease the use of raw materials in new construction. There are several established programs that address the reuse and recycle of materials: building deconstruction, construction materials salvage, and reuse of reclaimed materials in new site and building projects. Use of recycled materials decreases extraction of raw materials and reduces the embodied energy of a construction project. Recycling and reusing materials can also result in additional revenue and decreased costs in construction. Recycling is promoted by state and local municipalities through increased fees in landfill use and waste reduction laws.

Embodied Energy in Infrastructure Materials

Life cycle energy, or embodied energy, of a building can be divided into two categories: material and operating. Material embodied energy, the focus of this paper, can be defined as the sum of all the energy sequestered to produced, transport, and install a built asset. In some instances, it may include final demolition and disposal. Operational embodied energy is defined as the sum of all energy used in a building's operation during its life and includes heating, ventilation, and air conditioning (HVAC), water heating, lighting, and other equipment. The term CO_2

emissions, or embodied greenhouse gases, can be defined as the sum of all the greenhouse gases released from material extraction, transport, material manufacturing, building construction, disposal, and other related activities. Embodied energy is measured as energy per unit mass (joules/kilogram, J/kg) or energy per unit volume (joules/meter cubed, J/m^3), while CO_2 emissions is measured in mass of CO_2 per unit mass of product (kilogram of CO_2/kilogram, kg CO_2/kg). Although a building's embodied environmental impact can be expressed in terms of embodied energy or CO_2 emissions, it is more common to use an embodied energy measurement. There is a slight difference between CO_2 emissions and embodied energy as shown in Figure 1. While CO_2 emissions include all carbon released to the atmosphere in the production of the materials, embodied energy is the amount of energy consumed by all the processes used to manufacture the material.

Figure 1. *Total CO_2 and Embodied Energy in Various Materials in Concrete (Schokker 2012)*

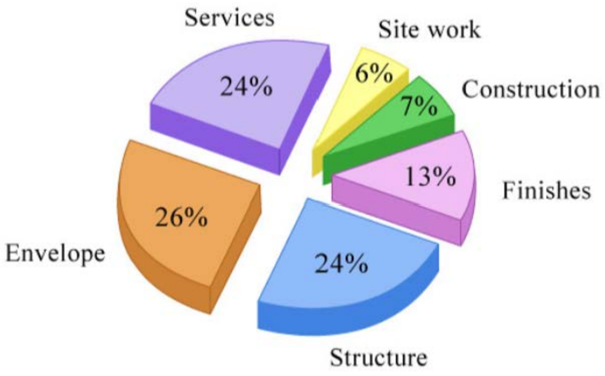


At first glance, structural engineers appear to have little to contribute to sustainability; however, Hays and Cocke (2009) make a compelling case to the contrary. It is argued that existing buildings can be repurposed to reduce embodied energy in construction materials as the greenest building is one that is already built. They present an embodied energy analysis of an adaptive reuse of a 1950's, two-story concrete warehouse. To construct a new building and replace the 4,645 square-meter space, it would require over 116 gigajoules (GJ) worth of energy: 59.6-GJ in the existing building, 0.818-GJ to demolish the building, and 59.6-GJ to construct the replacement building. A new high-efficiency building could not save this amount of energy over a fifty-year service life (Hays and Cocke 2009). Adams et al. (2010) present a breakdown of the initial total embodied energy per square meter in a typical building (4.82 gigajoules per square meter – GJ/m^2), with approximately a quarter of the embodied energy used in the structure (see Figure 2). These two examples illustrate how structural engineers can make substantial contributions to sustainability by retrofitting and repurposing existing buildings, and in cases where that is not possible, using structural materials with lower embodied energy content.

Concrete

Production of cement, the main ingredient in concrete, nearly doubled between 1990 and 2005, (Mehta and Meryman 2009). Annual cement consumption rates have continued to increase, resulting in double the consumption of cement in the past fifteen years. This also means that pollution levels from cement production have doubled over the past fifteen years. It is estimated that global cement consumption will increase by as much as 23% by 2050 (WGBC 2019).

Figure 2. *Breakdown of Embodied Energy of a Typical Building (Adams et al. 2010)*



Cement producers are under increased pressure from governments and consumers to reduce CO_2 emissions as most of the concrete total CO_2 comes from cement as shown in Figure 1. Reduction in cement content in concrete can be accomplished by modifying a concrete mix design to replace the higher CO_2 cement with Supplementary Cementing Materials (SCMs), such as finely ground limestone, recycled fly ash (i.e., a pozzolanic byproduct of coal-fired electricity generation), and blast-furnace slag (i.e., a pozzolanic byproduct of steel blast furnaces).

The benefits of using SCMs, particularly the pozzolanic byproducts, are twofold: the materials are diverted from the landfills and the cement's environmental impact is reduced because of its replacement with a carbon-neutral byproduct. This is a common practice in Europe where Portland-slag cements contain over 50% ground granulated-blast-furnace slag (Mehta and Meryman 2009). The Portland Cement Association (PCA) and the American Concrete Institute (ACI) have developed recommendations for limestone, fly ash, and slag cement replacement by weight (Table 2). According to PCA, fly ash and slag are optimal substitutes for raw cement because their use results in no degradation to the mechanical properties of concrete. This is particularly important since cement, on average, accounts for as much as 85% of the energy needed to produce concrete (Figure 1), but only makes up a small percentage of the mix, approximately 15%. Using these by-products and reusing some hardened concrete as aggregate can result in a material that is 50 to 60% recycled and much more energy efficient.

Table 2. *Recommendations for Supplementary Cementing Materials (SCMs)*

Product	PCA/ACI Recommended Replacement by Weight	Comments
Fly Ash Class C	15% – 40%	High calcium content This has pozzolanic and cementitious properties
Fly Ash Class F	15% – 25%	Low calcium content Pozzolanic, but little cementitious properties Primarily replaces fine aggregate
Slag	30% – 40%	Used in general concrete construction
Limestone	5% – 15%	5% can replaced clinker 5% to 15% used in blended cement
Silica Fume	Up to 30%	Used to make high-strength concrete

In normal concrete, a large portion of cement never hydrates because rapid reaction inhibits uniform cement distribution throughout the concrete material. This issue is more critical for early strength concrete since it cannot reach its full potential compressive strength at the specified age. Aiming to minimize the un-hydrated cement and produce a high-performance material, PCA has developed several admixtures to promote cement hydration and obtain a higher compressive strength sooner. High performance concrete also requires optimized aggregate gradations to produce a more impermeable hardened concrete that can prevent corrosive chemicals from reaching the steel reinforcement. This results in increased material durability. Thus, mix designs optimized for early strength and rapid construction can increase the concrete durability and lessen its environmental impact. Also, higher strength concrete results in smaller components for a given target capacity.

Until recently, the main impediment to reducing cement content in concrete was conventional industry standards. Such standards had institutionalized cement intensive mix designs that exhibited poor long-term performance and as a result, unnecessary adverse environmental impacts. However, since the concrete industry is organized around consensus standards and most professionals now recognize the importance of sustainability, sustainable practices are slowly being incorporated into the concrete industry. In fact, fly ash and slag American Standard for Testing and Materials (ASTM) standards (ASTM C618 and ASTM C989, respectively) have been developed as a testament to the concrete industry's commitment to sustainability. The steps being taken by the cement industry to reduce its carbon-footprint, particularly the use of SCMs, will result in concretes with lower embodied energy, lower carbon emissions, and lower environmental impact from the extraction and processing of virgin materials, and an increased diversion of by-product materials from landfills, all of which will result in a more cost-effective, durable concrete material with a much longer service life.

Steel

Steel has become a highly recycled material. By taking large amounts of scrap steel to manufacture new steel, it is the most recycled material today. Steel recycling and new processing methods have decreased its impact on the environment by as much as 75% over the past 75 years. In fact, at the end of a building's life, over 98% of all steel is recycled and reconstituted into new steel products (AISC 2011). Not only is steel 100% recyclable, but it can be multi-cycled without degradation to its mechanical properties, making it truly a cradle-to-cradle material unlike other materials that can only be recycled into a lower quality product or downcycled (AISC 2011). Furthermore, processing innovations have allowed the steel industry to produce steel that is 40% stronger than steel from half a century ago. Most steel today is produced by electric-arc furnace, which can use electricity produced from renewable sources, such as solar and wind. This will eventually permit the steel industry to attain its goal of producing steel that has no carbon footprint (i.e., zero-carbon steel).

Due to its cradle-to-cradle property, the energy consumption during steel production has decreased by as much as 75% over the past 75 years (AISC 2011). The most drastic change came in the 70's and 80's when the industry began using recycled steel and switching from coal burning furnaces to electricity. Over the past half century, various developments in the production of new steel have led to tremendous progress towards some of the most important goals of sustainability (e.g., promoting energy efficiency, reducing the use of virgin materials, minimizing site disturbance, and providing a healthier living environment). Considering its high strength-to-weight ratio, the carbon footprint from steel is relatively small, as little as 300-kg of CO_2 are produced to manufacture a ton of steel (Table 1).

Several advances in recent years have contributed to the reduction in the volume of steel used in any given project, particularly the development of high strength steel that has 40% higher strength (36 ksi to 50 ksi). This increase in strength results in smaller elements that in turn, results in smaller supporting superstructure and foundation components. Also, since steel has a high strength-to-weight ratio, it can carry large loads with a smaller structural system which reduces the impact of a building on the site by requiring less widespread site development.

The use of recycled steel also increases the volume of materials diverted from the landfills and repurposed. Byproduct materials that would typically result from extracting raw material from the ground are diverted from the landfills since virgin steel is replaced by recycled steel. Minimal steel waste is generated at fabrication facilities or construction sites as most waste generated is recycled. Additionally, when considering that steel buildings require minimal ongoing maintenance, have long lives, and are recyclable at the end of their life, the resulting environmental impact of steel is minimal. Furthermore, steel from deconstruction is made easier and faster because of the use of steel bolts to fasten steel systems. Figure 3 shows repurposed structural steel sections being used as shoring to support the construction of a concrete bridge.

Figure 3. *Repurposed Steel*

Other innovations in the design of steel buildings that can have a significant impact on their sustainability include:

- The use of a design-build approach which entails reducing the delivery schedule of a project by overlapping the design and construction phases. This compressed schedule also lessens the adverse effects of construction on the site.
- The use of Building Information Modeling (BIM) allows the designer to create 3-D computer models of all building systems to determine their interactions and conduct conflict resolutions before construction even begins. BIM can be used to optimize the integration of mechanical systems within the floor beams leading to lower floor-to-floor heights and resulting in less building volume to be heated or cooled. This lowers the building's energy consumption.
- Continuous improvement in water resource management in the production of steel has resulted in a 95% water recycling rate; currently, less than 70 gallons of water are consumed per ton of steel produced (AISC 2011).
- With concern for indoor environmental quality, steel framing systems can be used to span large indoor areas to improve occupant comfort. Such systems can also span large wall openings for windows to allow natural lighting which can result in a reduction in electrical consumption and further reductions in CO_2 emissions.

Initiatives in place reduce steel's carbon-footprint, particularly with high-strength steel, new innovative design techniques, and recycling and reusing steel. This results in increased diversion of byproduct materials from landfills and more importantly, buildings with a lower embodied energy, lower CO_2 emissions, and lower environmental impact from the extraction and processing of virgin materials. The steps already taken and future developments will make steel a more sustainable and cost-effective material.

Timber

Timber construction has had the most significant impact on the environment, both positive and negative. Until third-party certified sustainably harvested wood became available, timber production resulted in soil erosion, pollutant runoff, increased CO_2 levels, and habitat loss. Timber that comes from certified forests has been managed to maximize timber yield, promote healthy ecosystems for wildlife habitat, and minimize erosion to protect waterways (DeStefano 2009). The certification programs best recognized in North America are the Forest Stewardship Council (FSC), the Sustainable Forestry Initiative (SFI), and the Program for the Endorsement of Forest Certification (PEFC).

Furthermore, wood farming mitigates the effect of clear-cutting old growth forests. These forests are harvested relatively frequently. The resulting smaller diameter trees can be used as structural wood and turned into Engineering Wood (EW) products, such as plywood, oriented-strand board panels, glued-laminated lumber, laminated and parallel strand lumber, and laminated veneer lumber. The most common binder used in EW products is phenol-formaldehyde resin which can make EW products more difficult to recycle. However, the potential adverse effects of engineered lumber are offset by the more efficient use of natural resources and potential use of recycled content.

Even though timber can be a renewable resource, only about a quarter of structural timber comes from certified, sustainably managed forests. However, significant progress has been made in recent years. In fact, because of reforestation practices, the forested area in North America is approximately the same size compared to 100 years ago. The net annual growth is three percent greater than harvests and other losses combined. On average, 98% of any given tree brought to a mill is used as timber, paper, engineered wood products, or fuel in the form of bioenergy (Ward 2010).

Timber can be considered a carbon negative material, at least in the short-term as noted in Table 1. Wood removes carbon from the atmosphere through photosynthesis (Falk 2010):

$$\text{Sunlight} + 6\,H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$$

namely, Energy + Water + Carbon dioxide → Glucose + Oxygen. Thus, not only can a substantial amount of CO_2 be sequestered, but oxygen can be released. For every pound of CO_2 removed from the atmosphere (i.e., sequestered through photosynthesis when a pound of timber is grown), 0.73 pounds of O_2 are released. If timber is burned or decomposes, the process is reversed, releasing the CO_2 back into the atmosphere and yielding a net carbon emission which is still the lowest CO_2 emission of all construction materials (Table 1).

Because wood requires low energy during processing and more than 60% of this energy comes from biofuel, a carbon-neutral energy source, the embodied energy in timber is much lower than other construction materials (Falk 2010). Half of the energy required to produce lumber goes into drying the wood in a kiln. Specifying green, un-dried lumber is 50% more energy efficient. Though higher than sawn lumber due to the processing involved, EW products have a relatively low embodied energy. However, EW products, such as oriented strand board and composite lumber, use wood chips manufactured from smaller trees from shorter rotation harvests. These trees sequester more CO_2 than those in longer-rotation forests (Falk 2010). This balances some of the additional embodied energy required to process EW products.

Unlike the commonplace process of recycling pre- and post-consumer steel for structural applications, timber recycling is primarily used as biofuel. Nonetheless, timber reuse from deconstruction is possible, though more complicated than for steel. Reusing post-consumer recycled timber for structural purposes requires the timber to be re-graded according to standardized grading rules, and in some cases, tested. Recycled wood can be processed into landscape mulch which is useful to retain moisture in the soil and lessen the water demands from plants.

Masonry

Masonry can be divided into categories based on application (i.e., structural and non-structural) and material (i.e., concrete, clay, and fly ash). In structural applications, masonry is used primarily as walls which can serve as combined gravity and lateral load-bearing elements. To serve this purpose, masonry walls must be reinforced with steel, though many un-reinforced clay masonry walls were built in the past and are still standing. Masonry in the form of concrete masonry units (CMU) is the most common form of masonry structural walls, while brick (clay, concrete, or fly ash) is almost exclusively used for facing buildings. Prefabricated CMU cellular elements serve as formwork for the concrete walls, eliminating the need to use timber formwork. This, however, is increasingly uncommon because the process of assembling a masonry wall is labor-intensive and more efficient methods have been developed to construct concrete walls, including site cast, tilt-up, or precast walls.

As for non-structural applications, exterior facing masonry walls can serve to provide thermal mass. This also applies to concrete walls. Depending on the thickness of the wall, this can markedly improve the thermal performance of a building. The process entails absorbing energy from the sun during the daylight hours and releasing it as radiant heat at night. This lessens the effect of temperature swings within the building envelope, and for much of the year in many parts of the world, maintains thermal comfort without the need for heating or air-conditioning.

From a sustainability standpoint, masonry can be used in permeable pavement applications. Masonry as concrete, clay, or fly ash units can improve the storm water management of a site by providing a permeable material for storm water infiltration over a hard surface. This type of permeable pavement system can also reduce surface runoff by improving the soil percolation of a site.

The masonry industry has made great progress in reducing the embodied energy of its products, particularly that of brick. Brick continues to be one of the most popular building facing materials because of its classic beauty, high thermal and acoustic mass, and durability. The industry is expected to continue promoting practices that will reduce its carbon-footprint, such as minimizing the use of cement in CMU and replacing fired clay brick with more sustainable fly ash brick.

Advanced Composite Materials

While there has been much research and interest over the past few decades, advanced composite materials have had limited use in infrastructure applications when compared to traditional infrastructure materials. Typically, they are used as retrofit components or components targeted to address specific issues, such as corrosion in steel reinforced concrete. The main advantages of composites over their conventional counterparts are their high structural performance, high specific mechanical properties, and durability. The most common applications for composites to date include rehabilitation of structures, seismic retrofitting of columns, and bridge decks. Most of these applications of composites are intended to extend the life of structural systems well beyond their expected life, which may, in many cases, balance their adverse environmental effects.

As shown in Table 1, FRP has a very large carbon footprint. When compared to aluminum or steel parts made from average recycled content, composite parts' embodied energy is much higher. However, a study based on life-cycle analysis of structural components fabricated by Strongwell Composites indicates that the embodied energy of some composite components is lower than that of steel members made from virgin materials (Black 2010). The report suggests that this is primarily due to the composites' superior specific properties, such as high strength-to-weight and high stiffness-to-weight ratios.

One other area where composites stand to have a significant positive impact on the environment is renewable energy systems, particularly wind power. To harness the power from wind, large turbines are placed on high towers. The turbine blades must be relatively light for transportation and efficient operation which is why most turbine blades are manufactured using composites. In 2007, more than 17,000 turbines (nearly 50,000 blades) were in operation around the world for a total capacity of 94,112 megawatts. This constitutes the largest single applications of engineered composites in the world (Hollaway 2010). The Global Wind Energy Council tracks the global wind power growth and reported the 2020 wind power capacity at 743,000 megawatts, which is equivalent to a reduction in CO_2 emissions equivalent to the annual emissions produced in South America.

Comparison of the Embodied Energies in Infrastructure Materials

Table 3 shows the density, strength, stiffness, and specific properties (i.e., a ratio of the strength-to-density and stiffness-to-density) for the various materials listed in Table 1. To properly compare materials from a structural standpoint, an indexing approach is typically used that accounts for the vast differences in material strength, stiffness, and density. For example, a kilogram of steel is much stronger and stiffer than a kilogram of concrete. However, dividing by densities, material properties can more properly be compared. Inspection of Table 3 clearly indicates that FRP composites have the best performance from a structural standpoint, followed by steel and timber. Concrete has similar properties to timber based on the effective properties of the two materials. This approach is widely used in fiber reinforced composite materials when comparing their properties to those of traditional construction materials. A similar analysis can also be performed in terms of cost to identify the most economical design. The approach in this paper is applied to compare the ecological properties of various materials.

Table 3. *Comparison of Effective Structural Properties for Various Materials*

Material [a]	**Ave. Density, ρ kg/m^3**	**Strength, σ MPa**	**Stiffness, E GPa**	**Specific properties (MPa*m^3/kg)**	
				σ/ρ	**E/ρ**
Aggregate	2300	-	-	-	-
Portland Cement	1500	-	-	-	-
Concrete	2400	35	30	0.015	12.5
Steel (100% recycled)	7800	350	210	0.045	26.9
Lumber (Douglas Fir)	450	6.9	13.1	0.015	29.1
Concrete blocks	1500	13.5	3.75	0.009	2.5
Common Brick	1700	7	4	0.004	2.4
GFRP (45% Epoxy)	1800	40	870	0.022	483.3
CFRP (50% Epoxy)	1500	142	1730	0.095	1153.3

[a] Values are from various sources (primarily form Crawford, 2019 and Ashby, 2009) and are based on life cycle analyses.

Table 4 provides a comparison of the various ecological properties of materials discussed in this paper with strength and stiffness divided by the materials' embodied energy and labeled as Specific EE. Concrete and steel are comparable in their ecological strength and stiffness, and though timber has traditionally been considered the most sustainable material, its specific EE places it third to concrete and steel. As expected, FRP composites have low specific EE values indicating their limited contribution to a sustainable build environment, which is why they are employed only in very specialized applications where they can be shown to be advantageous from an economical or sustainable standpoint. It is important to note that values in Table 4 are preliminary and should only be used as a guide. Published values for the embodied energy of materials vary widely and an effort was made here to utilize accurate values. As values for the various materials become more precise, the analysis based on effective ecological properties can be utilized as another method of comparison.

Traditionally, lightweight structural building materials have been considered to have low embodied energy compared to their heavier counterparts. However, as shown in Tables 3 and 4, this is not necessarily the case and designers should consider effective ecological strength and stiffness properties. Also, as discussed in the masonry section, there are climates with relatively large HVAC demands (i.e., significant variations in day-night temperatures) where a high level of thermal mass can offset the energy required for HVAC. Designers should balance the building energy requirements according to geography, climate, and availability of local materials, all of which should be accounted for in a life cycle analysis. Other guidelines to address sustainability during design and construction phases include:

- specifying recycled materials or materials that come from sustainably managed sources that have low embodied energy,
- reusing parts of demolished structures (deconstruction),
- using Supplementary Cementing Materials to produce "green" concrete,
- specifying locally sourced materials to reduce transportation costs and emissions,
- using durable, low maintenance materials, that can easily be refurbished or repurposed,
- specifying non-toxic material preservatives that can easily be separated and salvaged,
- using prefabricated components whenever possible,
- designing structures that can be altered and can be adapted to new uses (reuse) or loading conditions,
- specifying materials that create an efficient building envelope that can downsize or eliminate the need for HVAC
- requiring that construction site waste and demolition debris be sorted and recycled or used as biofuel, and
- specifying materials that have been produced using renewable energy sources, such as wind or solar.

Table 4. *Comparison of Effective Ecological Properties for Various Materials*

Material [a]	**Embodied Energy (EE)**		**Specific EE (MPa/MJ/kg)**	
	GJ/m^3	**MJ/kg** [a]	**σ/EE**	**E/EE**
Aggregate	0.19	0.083	-	-
Portland Cement	17.7	11.8	-	-
Concrete	2.7	1.13	31.11	26667
Steel (100% recycled)	76.4	9.8	35.71	21429
Lumber (Douglas Fir)	1	1.4	4.93	9357
Concrete blocks	0.96	2.6	5.19	1442
Common brick	11	3	2.33	1333
GFRP (45% Epoxy)	540	300	0.13	2900
CFRP (50% Epoxy)	800	533	0.27	3244

[a] Values are from various sources (primarily form Crawford, 2019 and Ashby, 2009) and are based on life cycle analyses.

Conclusions

The adverse environmental impact of new infrastructure systems can be minimized by using sustainable practices in infrastructure design. More sustainable methods in the fabrication of construction materials (e.g., concrete, steel, timber, masonry, and FRP composites) can also drastically lower the overall construction cost, particularly when direct and indirect costs over the life of the system are considered. Life Cycle Assessment is the best approach to assess sustainability

(Hsu 2010). Without incorporating sustainability in construction, the adverse environmental effects from concrete and steel consumption would have continued to increase. However, if CO_2 emissions are not reduced further, the environment will continue to suffer, threatening the long-term welfare and health of the public which are within the purview of building codes.

Carbon emissions in cement (and concrete) production is of great concern because 60% of these emissions come from the calcination process. A temporary remedy for this issue is to incorporate more Supplementary Cementing Materials like fly ash in concrete. A more permanent solution is to find alternative carbon-neutral cementitious materials and ultimately lower the overall embodied energy in concrete. There are several researchers working on such a material, dubbed "green concrete". Steel is another construction material widely used in infrastructure. Its cradle-to-cradle property allows recycling to be done without affecting its performance while at the same time, reducing manufacturing costs and the impact to the environment. The timber industry has had the greatest impact on sustainability practices because the material can be considered a renewable resource. Furthermore, the industry has embraced sustainability practices at all levels, from harvesting to construction. Masonry and composites make up a very small percentage of materials used in construction; thus, any improvement in their sustainability can be considered insignificant compared to concrete, steel, and timber.

Both the concrete and steel industries have dramatically changed over time due to institutionalized groups, such as AISC, PCA, ACI, and LEED. Their collaborations with various other groups have allowed sustainability to be more accepted worldwide. These groups have redefined the role of engineers and have changed standards that have resulted in improved environmental policies.

Acknowledgments

We would like to thank Lariel Joy Mateo for her proofreading and extensive editing of the entire manuscript.

References

Adams E, Connor J, Ochsendorf J (2010) *Embodied energy and operating energy for buildings: cumulative energy over time*. Cambridge, MA: Massachusetts Institute of Technology.

American Institute of Steel Construction – AISC (2011) *The sustainable aspects of structural steel*. Available at: https://bit.ly/410kEnf.

Ashby MF (2009) *Materials and the environment: eco-informed material choice*. Canada: Elsevier Science & Technology.

ASTM C618 *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete.* West Conshohocken, PA: ASTM International.

ASTM C989 *Standard specification for slag cement for use in concrete and mortars*. West Conshohocken, PA: ASTM International.

Black S (2010, November 30) *Life cycle assessment: are composites "green"?* Composites World.

Crawford R, Stephan A, Prideaux F (2019) *Environmental performance in construction: a database of embodied environmental flow coefficients*. EPiC Database.

DeStefano S (2009) *Wildlife corridors and developed landscapes*. In A Esparza, G McPherson (eds.), *The Planner's Guide to Natural Resources Conservation*. New York, NY: Springer.

Falk RH (2010) Chapter 01: Wood as a sustainable building material. In *Wood Handbook: Wood as an Engineering Material*, General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Hays B, Cocke D (2009) *Missed opportunities in structural engineering*. Structure magazine, A joint publication of NCSEA/CASE/SEI, April 2009.

Hollaway LC (2010) A review of the present and future utilization of FRP composites in the civil infrastructure with reference to their important in-service properties. *Construction and Building Materials* 24(12): 2419–2445.

Hsu SL (2010) *Life cycle assessment of materials and construction in commercial structures: variability and limitations*. Massachusetts Institute of Technology.

IPCC (2018) *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* Edited by V Masson-Delmotte, P Zhai, H-O Pörtner, D Roberts, J Skea, PR Shukla, et al. Cambridge, UK and New York, NY, USA: Cambridge University Press.

Kneer E, Maclise L (2008) Consideration of building performance in sustainable design: a structural engineer's role. In *Procedings of the 2008 SEAOC (Structural Engineers Association of California) Convention*.

Mehta PK, Meryman H (2009) *Tools for reducing carbon emissions due to cement consumption*. Structure magazine, A joint publication of NCSEA/CASE/SEI, January 2009.

Miller N, Spivey J, Florance A (2008) Does green pay off? *Journal of Real Estate Portfolio Management* 14(4): 385–400.

Pade C, Guimaraes M (2007) The CO_2 uptake of concrete in a 100-year perspective. *Cement and Concrete Research* 37(9): 1348 –1356.

Schokker AJ (2012) *The sustainable concrete guide: applications*. Farmington Hills, MI: U.S. Green Concrete Council.

U.S. Environmental Protection Agency – EPA (2009) *Estimating 2003 building-related construction and demolition materials amounts*. EPA530-R-09-002.

Ward R (2010) *Can using more wood reduce your environmental footprint?"* Structure magazine, A joint publication of NCSEA/CASE/SEI, February 2010.

World Green Building Council – WGBC (2019) *Bringing embodied carbon upfront; coordinated action for the building and construction sector to tackle embodied carbon.* WGBC.

Athens Journal of Technology and Engineering - Volume 10, Issue 2, June 2023 – Pages 123-134

Utilising Magnus Effect to Increase Downforce in Motorsport

By Mark Lin, Patrick Lewis± & Periklis Papadopoulos°*

The Magnus effect is the generation of a sidewise force on a spinning cylindrical or spherical solid immersed in a fluid (liquid or gas) when there is relative motion between the spinning body and the fluid. This is most commonly seen in baseball, tennis, or European football where the ball's trajectory is curved due to its rotation. The idea of using the Magnus effect in an airfoil to produce lift was proposed in 1941 in a patent application by Massey. This is also known as Kutta–Joukowski lift, first analyzed by Kutta and Joulowski in the late 19th century. In maritime applications, it is known as Flettner rotor sails, first used in the 1920's. Although Magnus effect is not new, the idea of using it on a racecar wing to improve downforce has not been extensively studied. The concept is to replace the front leading-edge of the wing with a rotating cylinder of the same diameter to produce additional circulation around the foil. This idea was born out of discussion at San Jose State University's Formula SAE team as a way to create variable downforce on their wings. Although the idea was proposed but it was never built because of the complexity in the construction and a lack of rigorous analysis. Subsequently from our CFD simulation, it shows that by imposing a +2U angular velocity to the front LE cap (i.e., rotating upwards in the negative-x direction), we could gain 4.25% of downforce. Since the leading edge cap is roughly cylindrical, physically replacing it by a cylinder would not cause a visible change to the race car's geometry while improving the aerodynamics using Magnus effect. This CFD data show promise to take the next step of building a physical prototype and perform aerodynamic experiments to validate this finding.

Keywords: *Magnus effect, aerodynamics, downforce, CFD, motorsport.*

Introduction

Magnus effect is a term used to describe the aerodynamic force imparted on an object while it is spinning. This in turn would affect the trajectory of the object. It is named after Heinrich Gustav Magnus, the German scientist who investigated it in the mid 1800's. One good example of the Magnus effect is a "curve ball" thrown by an American baseball pitcher. Why does the ball path curve? Because the ball is spinning. This IS the Magnus effect. Another good demonstration of this effect is the YouTube video by Veritasium (2015), which shows the distance travelled when a basketball is dropped from a tall dam with and without spin. We see this effect all over sports every day, from European football to golf to

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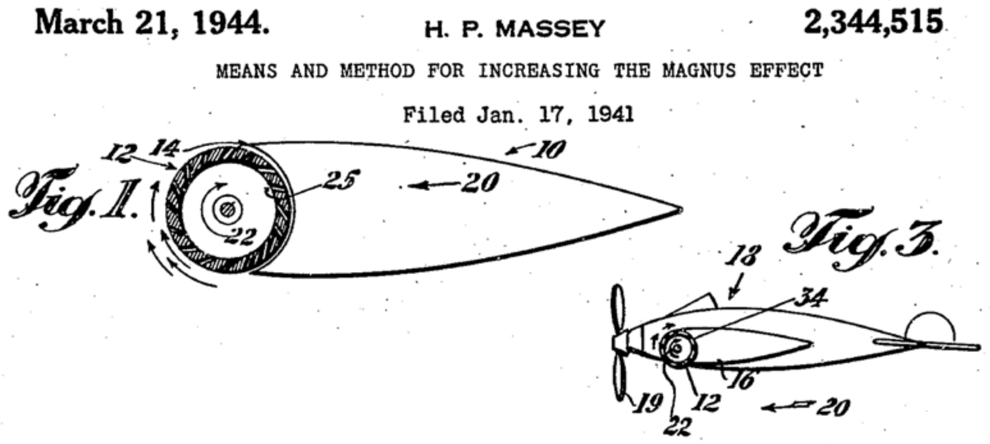
volleyball. However, usage of the Magnus effect in other industries is less frequently seen. This paper studies the application of the Magnus effect to motorsport to further expand the automotive design envelope and performance. This is especially true in Formula racing, where a predefined formula homologates the design of the cars to ensure competition fairness. However, if the Magnus effect can be made to work it would be especially advantageous. This study investigates the idea using Computational Fluid Dynamics.

Literature Review

The first idea of utilising a rotating cylinder for the leading edge of an airfoil was seen in a 1944 patent by Massey. Figure 1 shows the patent drawing that illustrates the utility of such a device in aviation. Hence, the idea is not new as it has been proposed for use back in the 1940's.

Figure 1. *1944 US Patent of Magnus Effect on Airfoils*



Subsequent to this proposal, the Magnus effect has not really been seen much in the aviation industry as noted by Seifert (2012). He commented while it has been used in the shipping industry, it has not really been adapted to the aeronautic industry. In recent years, a resurgence in using Magnus effect in aviation has resulted in YouTube videos, in particular the *KFC Bucket Aeroplane* (Sripol 2017) and another video about *Building an Advanced Magnus Effect Plane* from the UK (ProjectAir 2021). However, both videos use only RC radio-controlled models instead of full-scale implementation. As far as analysis goes, Dharmendra et al. (2021) and Patkunam et al. (2015) showed how Magnus effect can increase lift on an aircraft wing using CFD simulation. Another two papers that are more theoretical look specifically at the Magnus effect on a spinning cylinder (Gowree and Prince 2012, Stafy and Neto 2016). Overall, there has not been many publications showing practical aeronautical applications of the Magnus effect, whereas in marine applications commercial use of the Magnus effect is demonstrated in the shipping industry as the Flettner Rotor (MarineInsight 2021). It was first used in maritime in the 1920's as shown in Figure 2.

Figure 2. *Flettner Rotor used in Maritime Applications*

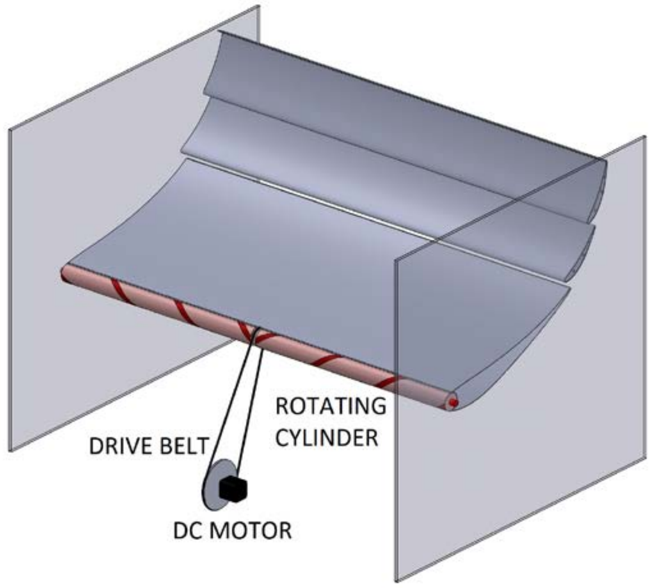
The idea of using Magnus effect for ship propulsion continues today with companies such as Norsepower Ltd. (2017) where large oceanliners are fitted with tall vertical cylinders. With these references, it is noteworthy that while there have been commercial demonstrations in the shipping and aviation industries, in the automotive industry it has only been discussed to some extent (Angiras et al. 2022, Saward 2012, Kamal et al. 2015) and no extensive fluid dynamic analyses as presented in this paper. Even though the Magnus effect has not seen wide commercial adaptation, we actually see its effect in sports every day. A paper by Lyu and Smith on The Reverse Magnus Effect in Golf Balls is a good experimental approach to relate the backspin of the golf ball to its trajectory (Lyu et al. 2020). By putting dimples on the golf ball they would induce turbulence and reduce wake. Another paper titled The Magnus Effect in Volleyball Service by Video Analysis (Martins et al. 2021) in the European Journal of Physics is also a good demonstration of the Magnus effect. Finally, a paper by Kenyon (2016) provides an attempt to derive equations for the Magnus effect using Bernoulli's equation. While it is a good approach, the derived formula would be limited because Bernoulli's equation is for inviscid flow while the Magnus effect is largely a viscous boundary layer phenomenon.

Methodology

To explore the Magnus effect for application in motorsport, first a design to implement the mechanism on a racecar wing needs to be proposed. This is to give a visual picture of how downforce can be generated using Magnus effect. Next, the aerodynamic behavior needs to be simulated using Computational Fluid Dynamics to relate the mechanism’s rotational velocity to the resulting downforce produced, which we will present in the results section.

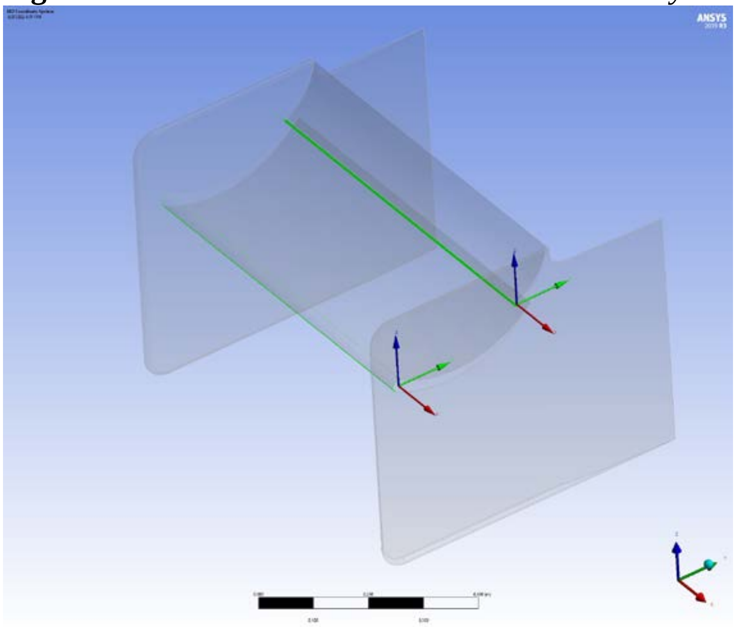
A physical design is shown in Figure 3: instead of a wing with a fixed leading edge, it is replaced by a rotating cylinder mounted on bearings to the endplate on either ends. To drive the cylinder, a belt or a chain is looped around an electric motor mounted on the chassis. A more sophisticated implementation would be to hide the belt/chain inside the endplate using a cutout, since the endplate is typically made of sandwich material. However, for simplicity only this implementation is shown here.

Figure 3. *Conceptual Design Illustrating Magnus Effect Implementation on Race Car Wing*



The foregoing paragraph describes an implementation of a Magnus effects wing in the physical form; to analyze it in CFD we need to idealize the geometry to have only a representation of the functional components. The geometry we choose to represent the wing and to analyze the Magnus effect is shown in Figure 4. This is a simple geometry that has 2 airfoils - a main element and a flap. On both ends is the vertical endplate. This geometry was used previously in a 2020 paper presented at the 4th ATINER Mechanical Engineering Conference. For this study we separate out the leading-edge caps so a moving boundary condition can be applied to simulate a rotating cylinder. For each leading-edge cap, a local coordinate system is defined for each cylindrical geometry to specify an angular velocity. Because the diameters of the two caps are different, each cylinder is specified with a different angular velocity so that the tangential velocity of the cylinder would be the same as the incoming fluid velocity, denoted by the symbol U. Before a volume mesh is generated, a thin surface inflation layer is prescribed to the wing's surface so that the boundary layer can be accurately modelled, because for Magnus effect it is all about the relative motion between the rotating surface and the adjacent fluid. In CFD the boundary layer is modelled using the wall model (aka. law of the wall). After the fluid domain is meshed, it is solved using ANSYS Fluent.

Figure 4. *Idealized CFD Model Used in Current Analysis*



In the solver, boundary conditions are first applied to the mesh. For the two leading-edge caps: angular velocity (in rad/s), local coordinate frame, and axis of rotation are first specified. As will be seen, performing Magnus effect analysis is very simple in CFD because we only need to change the boundary specification from a stationary wall to a moving wall, and indicate the velocity as angular instead of linear; otherwise the mesh is exactly the same as a stationary wall case. In the analysis, we do not need to have a separate cylindrical geometry or a rotating/ sliding mesh - one can simply achieve the same effect by changing the boundary condition. Since the free stream velocity (150 kph or 41.666 m/s) puts us in the turbulent flow regime, a turbulence model is used to simulate the flow for us to plot the pressure contour and streamlines. The turbulence model used is Transition SST (4 equations) to capture the transition from laminar to turbulent flow as air moves across the surfaces of the airfoil. The model is ran to 1000 iteration, where we have verified that the residuals have stabilized and the final solution is reached. Later on we will see, as the velocity is increased the solver will become unstable where the residuals will jump up (as in Figure 13), and if we continue to run the solver the solution will diverge and the run will terminate.

Results

The CFD model is ran with different rotational velocities from minus 2U (spinning down) to positive 2U (spinning up). “Spinning down” is counterclockwise rotation and “spinning up” is clockwise rotation viewed along the -*Z* direction in the local coordinates shown in Figure 4. The results are plotted in Figures 5 through 10. In each figure, the pressure contour in the fluid region and the corresponding streamlines are plotted. From the results one can see a progression from rotating the cylinder downwards to rotating it upwards. One thing to note when it's rotating downwards: the streamlines that originally went to the upper side of the leading edge is dragged down to the lower side because of the spinning of the cylinder. It actually creates a recirculation region on the topside of the leading edge. As the rotation is reversed toward the upper surface, the pressure contour shows a lower pressure region forming on the bottom of the leading edge, as shown by the second airfoil flap in Figure 9 and 10. Looking at Figures 5 through 10, while the leading edge rotation is changing rapidly, the changes in the pressure contour is minimal which makes it not suitable to decipher the Magnus effect at work; however, the change in the streamlines is more clear and one can associate the change in the rotational direction to how the air particles are moving, and whether they end up on the upperside or the lower side of the airfoil.

Figure 5. *Pressure Contour and Streamlines for Down 2U Rotation*

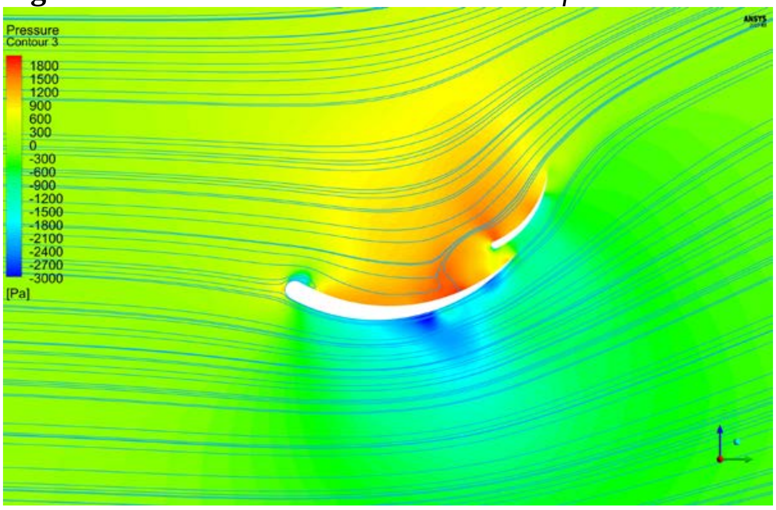


Figure 6. *Pressure Contour and Streamlines for Down 1.5U Rotation*

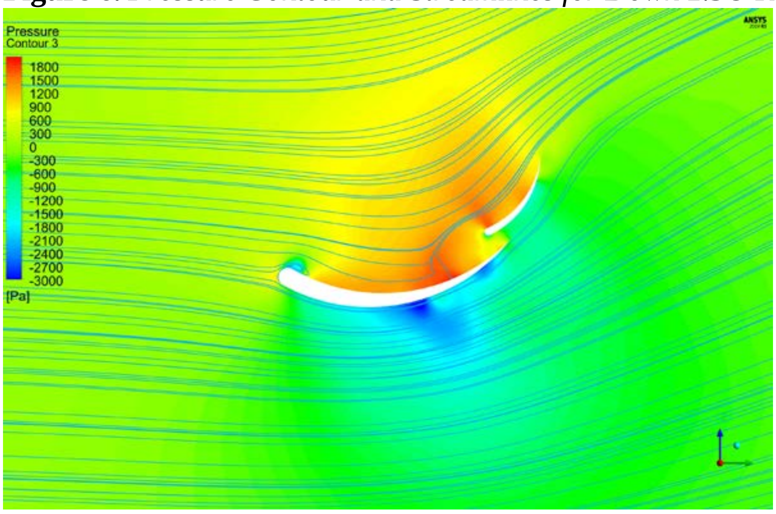


Figure 7. *Pressure Contour and Streamlines for Down 1U Rotation*

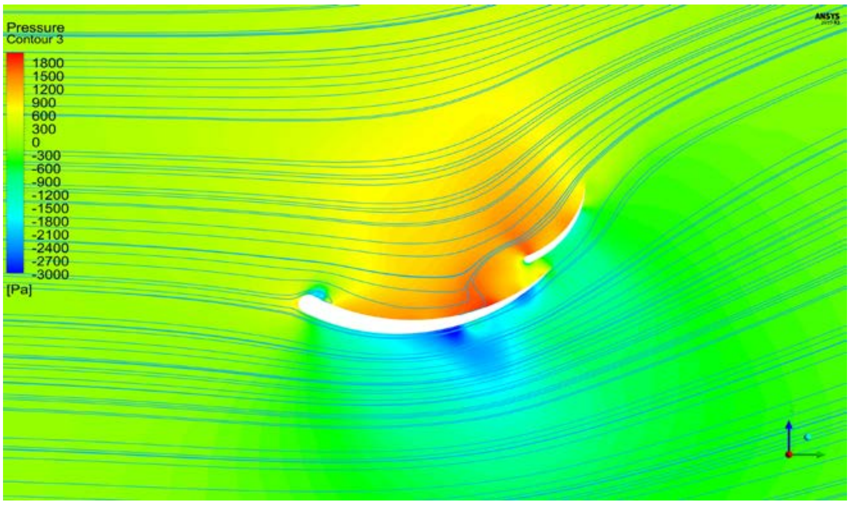


Figure 8. *Pressure Contour and Streamlines for No Rotation*

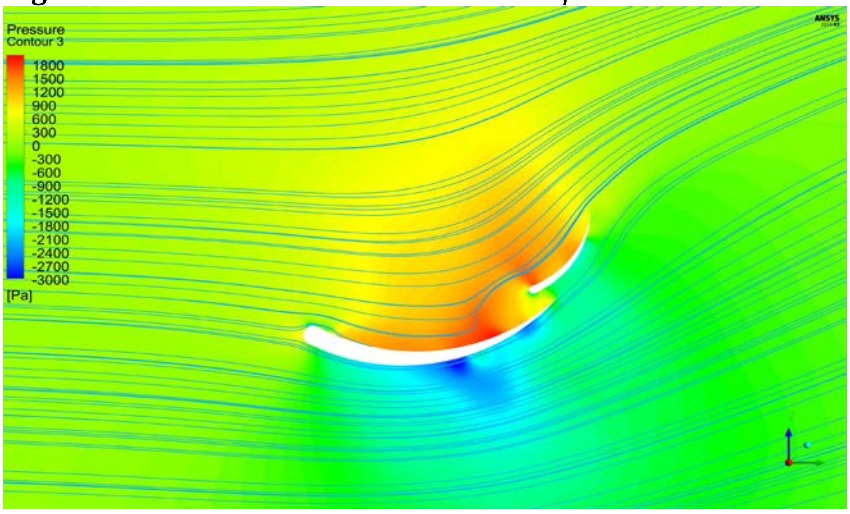


Figure 9. *Pressure Contour and Streamlines for Up 1U Rotation*

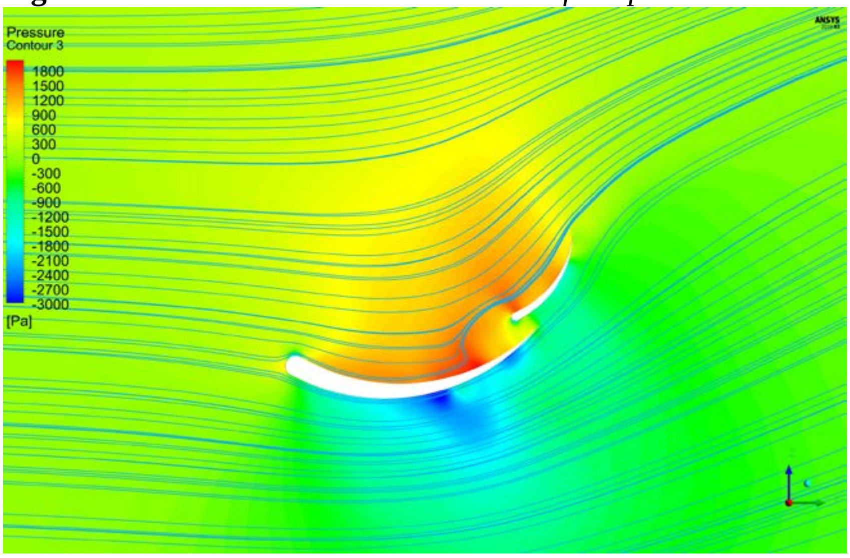


Figure 10. *Pressure Contour and Streamlines for Up 2U Rotation*

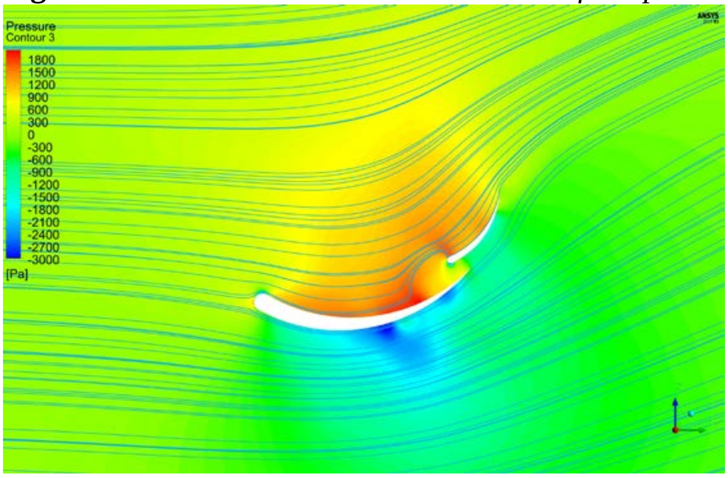
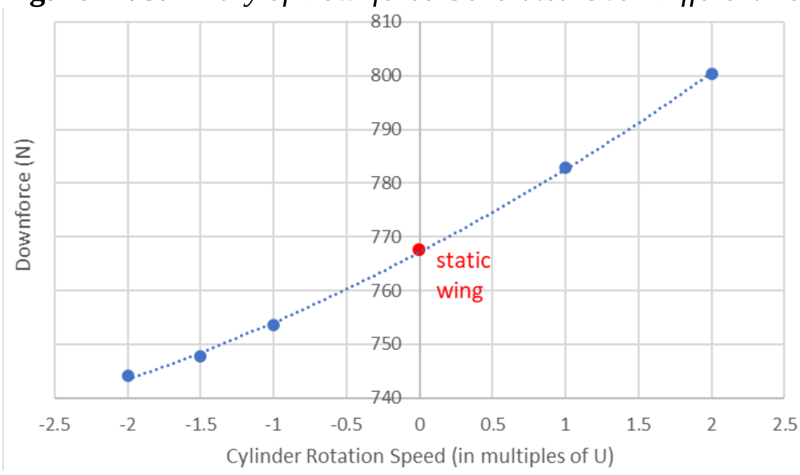


Figure 11 is a summary of the downforce predicted by the 6 cases shown in Figures 5-10. The downforce produced by these 6 cases is reported by CFD-POST in ANSYS Workbench. CFD-POST is the post processor for looking at CFD results. The downforce is obtained by going to the Calculators tab in CFD-POST and selecting *Function Calculator*. Next, *Force* is selected as the function and *Z* is selected as the direction. Finally, areas over the wing are selected individually and the results are summed together. The method by which it is obtained is to take the computed surface pressure, multiplies it by the surface area normal, and sums it over the entire surface. Each data point in Figure 11 represents an individual CFD run from a separate ANSYS Workbench project. When all the data are plotted together, it clearly shows a trend that when the cylinder is spinning upwards, more downforce is created on the wing. The baseline to which we are comparing this to is the wing with no motion, meaning without Magnus effect. In this plot, this shows that by spinning the cylinder upwards with a tangential velocity of 2U, meaning twice as fast as the freestream velocity, or twice the speed that the car is travelling, we can get a 4.25% increase in downforce. This is done with the same airfoil profile and will be unnoticeable to the untrained eyes.

Figure 11. *Summary of Downforce Generated Over Different Rotation Speeds*



Discussion

From these analytical results, let's explain what we are seeing using aerodynamic principles (Anderson 2011). One way to look at this is by looking at the boundary layer interaction between the wall surface and the free stream velocity. Using 3 cases as example: upward 1U rotation, no rotation, and downward 1U rotation. Figure 12 shows a schematic of these three cases. When there is no rotation fluid flow is equally parsed between the upperside and the lower side, with a stagnation point at the center of the radius. The boundary layer that develops is the same on both sides, by symmetry argument. Next, looking at the top schematic where the cylinder is spinning upwards with a velocity of 1U: now the top surface is moving at exactly the same speed as the freestream, therefore there is no relative motion between the surface and the fluid. Since wall shear stress is equal to the dynamic viscosity times the change of velocity in the y direction, which in this case is zero, the wall shear stress is zero on the top surface.

$$\tau = \mu \left(\frac{du}{dy}\right) \tag{1}$$

This means that the topside of the cylinder is in inviscid flow! Now flipping the direction of rotation to downward 1U and look at the bottom schematic: the lower side of the cylinder is now in inviscid flow. Next, let's look at the location of the stagnation point on the cylinder: if the cylinder is rotating upwards then the stagnation point moves down, indicating that more of the fluid goes to the topside of the cylinder; oppositely, when the cylinder is rotating downwards then the stagnation point moves up, indicating that more of the fluid goes to the bottom side of the cylinder. If we can use the spin of the cylinder to affect the amount of fluid going to the upper surface versus the lower surface of an airfoil, we will affect the amount of downforce that is created. This explains the Magnus effect at work on a racecar's wing.

Continue increasing the rotational velocity will eventually lead to solver instability as shown in Figure 13. This is a numerical problem and not a physical one. What it's telling us is that computationally the math has exceeded its limit so the solver cannot produce a reliable answer. In this situation, we refrain from drawing conclusions at the computational limit.

Figure 12. *Schematics of Boundary Layer for Different Rotation Speeds*

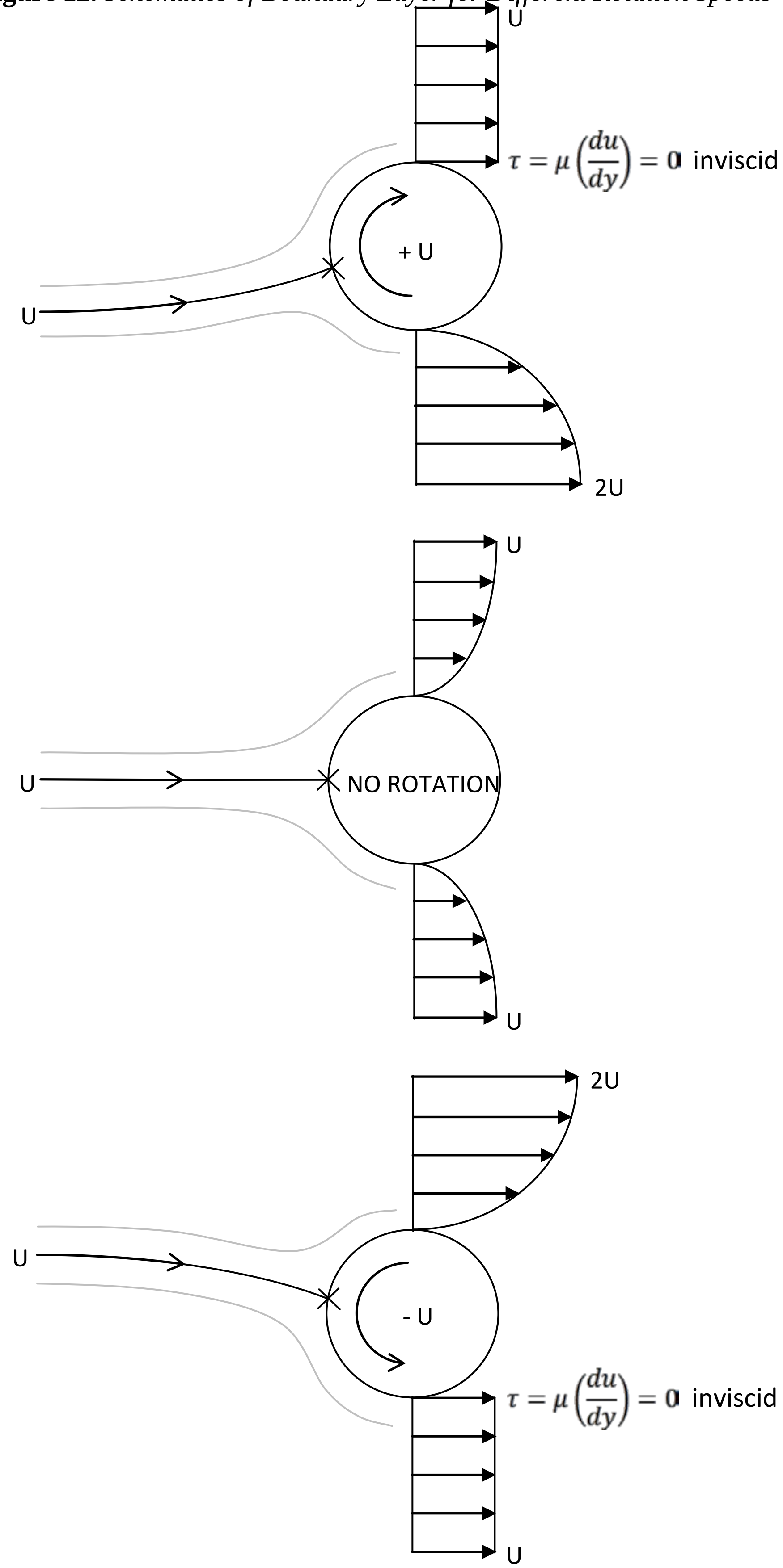
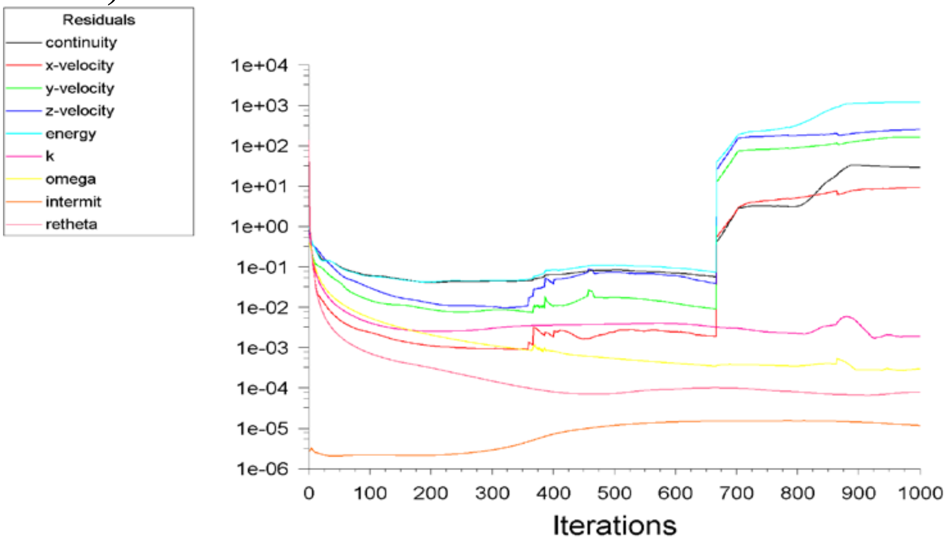


Figure 13. *Residual Plot when Calculation Does Not Converge (Case: Up 3U Rotation)*



Conclusions

Now that we have put forward an analysis utilising Computation Fluid Dynamics to illustrate the working of the Magnus effect, it is plausible that one can increase the amount of downforce on a racecar wing by imparting a rotational velocity on the leading edge with a cap cylinder. This is exactly the theory put forward in 1944 by Massey, albeit he did not have supporting data to show feasibility. This could be advantageous to racecars as each formula class has a prescribed geometry that the cars must conform to. With that said, there is currently no rule in the regulation that says the leading edge of the wing has to be stationary. And even if the homologation requires that, by rotating the cylinder at the same speed as the car, when the car is not moving the wing would also be stationary making it difficult to perceive a wing that incorporates Magnus effect. Some may argue that this gives an unfair advantage to the car that implements this device, but on the other hand advances in motorsport engineering often comes from innovations such as this. One should utilise the Magnus effect to increase downforce in motorsport.

Acknowledgments

The authors would like to thank San Jose State University's Aerospace Engineering Department and the College of Engineering's Formula SAE team for inspiration and support.

References

Anderson JD Jr (2011) *Fundamental of aerodynamics*. 5th Edition. McGraw-Hill Series.

Angiras V, Mishechkin M, Mularella J (2022) Utilizing the Magnus effect to produce more downforce than a standard wing. *Journal of Emerging Investigators* 5(15): 1–4.

Dharmendra P, Sullad P, Mallapur N (2021) Study of Magnus effect using rotating cylinder on airfoil at different locations. *Journal of Aeronautics & Aerospace Engineering* 10(11).

Gowree ER, Prince SA (2012) A computational study of the aerodynamics of a spinning cylinder in a crossflow of high Reynolds number. In *28th International Congress of the Aeronautical Sciences*, Brisbane, Australia, September 23-28.

Kamal R, Socrates S, Kaliappan S (2015) Aerodynamic effects on formula one car using CFD. *International Journal of Applied Engineering Research* 10(33): 28164–28172.

Kenyon KE (2016) On the Magnus effect. *Natural Science* 8(2): 49–52.

Lyu B, Kensrud J, Smith L (2020) The reverse Magnus effect in golf balls. *Sports Engineering* 23(3).

MarineInsight (2021) *Rotor sail explained*. YouTube Video. Available at: https://www.youtube.com/watch?v=FJt8l80kGTg.

Martins T, Bastos de Jesus VL, Sasaki DG (2021) The Magnus effect in volleyball service by video analysis. *European Journal of Physics* 43(1).

Massey HP (1944) *Means and method for increasing the Magnus effect*. U.S. Patent 2,344,515.

Norsepower Ltd (2017) *Norsepower rotor sail solution - long presentation video*. YouTube Video. Available at: https://www.youtube.com/watch?v=kDyBrSW1_Og.

Patkunam K et al. (2015) Experimental study of Magnus effect over an aircraft wing, *International Journal of Research in Engineering and Technology* 4(10): 406–414.

ProjectAir (2021) *Building an advanced Magnus effect plane*. YouTube Video. Available at: https:// www.youtube.com/watch?v=UG2O_GK7-R8.

Saward J (2012) *The secret of F1 aerodynamics in 2012*. JoeblogsF1. Available at: https://joesaward.wordpress.com/2012/03/14/the-secret-of-f1-aerodynamics-in-2012.

Seifert J (2012) A review of the Magnus effect in Aeronautics. *Progress in Aerospace Sciences* 55(Nov): 17–45.

Sripol P (2017) *RC KFC bucket aeroplane (Magnus effect)*. YouTube Video. Available at: https://www.youtube.com/watch?v=K6geOms33Dk.

Stafy V, Neto AS (2016) Study about Magnus effect on spinning cylinders and its use on micro air vehicles. In *Proceedings of the XXXVII Iberian Latin-American Congress on Computational Methods in Engineering*, Brasilia, DF, Brazil, November 6-9.

Veritasium (2015) *Backspin basketball flies off dam*. YouTube Video. Available at: https://www.youtube.com/watch?v=2OSrvzNW9FE.

Athens Journal of Technology and Engineering - Volume 10, Issue 2, June 2023 – Pages 135-146

Impact of Hull Fouling on Vessel's Fuel Consumption and Emissions Based on a Simulation Model

By Zoran Pavin[*] & Vlatko Knežević[±]

With an ever-increasing trend of analysing and improving vessel energy and economic efficiency in recent years and decades, every aspect of a vessel's system needs to be observed with the goal of reducing fuel consumption and emissions. Hull fouling can have a significant effect on these variables. Since hull maintenance is an expensive effort, its use must be optimized and fine-tuned to increase the economic efficiency of a vessel's exploitation cycle. In order to do this, data and a subsequent analysis have to be obtained on different stages of the hull fouling process and the effect these states have on vessel energy efficiency and consequently emissions and economic efficiency. This paper will analyse a set of data including emission pollutants such as nitrogen oxides (NO_X) and carbon dioxide (CO_2) as a greenhouse gas and the effect that different amounts of hull fouling have on the vessel's fuel consumption and emissions under different propulsion loads. The aforementioned data is obtained from a simulation model of a RoPax vessel. The advantage of using data from a simulation model of a RoPax vessel for the research discussed in this paper is the ability to analyse various conditions not easily reproduced on actual ships. Main research findings presented in this paper are consistent in proving that increased hull fouling leads to increased fuel consumption and emissions as high as 15% increase in extreme cases.

Keywords: *hull fouling, fuel consumption, pollutant, greenhouse gas, emissions, simulator*

Introduction

Due to new stringent regulations on ship's exhaust emissions and greenhouse gases, the shipping industry is trying to enhance energy efficiency and optimize fuel consumption with different measures. One of the main reasons for the fuel oil consumption increase is hull and propeller biofouling. The term fouling is generally used to describe the settlement of marine plants and microorganisms on the hull surface which leads to an increase in hydrodynamic hull resistance, ship drag and fuel consumption (Oliveira and Granhag 2020). This problem was recognized by the International Maritime Organization (IMO) which resulted in a Marine Environment Protection Committee Resolution MEPC 207(62) for the control and management of ships biofouling. Nowadays, most of the newer ships have installed anti-fouling systems on board and hull coatings, however some ships have prolonged time at berth so fouling could develop quickly.

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The analysis of power loss and increased fuel consumption from the economical point of view is presented in an article with a conclusion that voyage delay and fuel consumption are impacted by the ship's state (Giorgiutti et al. 2014). The engine performance degradation due to hull fouling is emphasized in the article where results have shown that 10% of fuel costs could be saved with efficient dry dock treatment (Munk 2006). The increase of propeller shaft torque caused by hull fouling is analyzed in the paper (Tarelko 2014). This problem is changing the structure of water flow which results in affecting propeller performance and efficiency. The increased hull resistance is also affecting the operating conditions of the crankshaft, pistons, cylinder cover, thrust bearings and turbocharger (Dere et al. 2016). Figure 1 presents the layer of marine plants and organisms on the ship's hull. The goal of this paper is to analyze how different percentages of hull fouling are affecting the ship's speed, fuel consumption and amount of air pollutants such as nitrogen oxides and carbon dioxides.

Figure 1. *Fouled Hull Before Cleaning*[1]

Methodology

The simulator used for the research in this paper is Wärtsilä ERS-LCHS 5000 TechSim engine room simulator, owned by the Maritime department of the University of Zadar. The modelled vessel is a RoPax ferry with twin four stroke medium speed non-reversible MAN B&W 8L32/40 diesel engines and controllable pitch propellers [8]. The ship model particulars are shown in Figure 2. This

[1]https://www.we4sea.com/blog/the-effect-of-a-hull-cleaning-and-how-to-measure-it. (last accessed on 24.05.2022).

specific simulator model was based on an actual vessel (Bornholms Trafikken RoPax Ferry) and was validated against measurements taken on actual RoPax ferries sailing in the Adriatic Sea on routes between Italy and Croatia (Orović et al. 2022).

Some of the many features of the aforementioned simulator model are introducing various environmental and fault variables during vessel navigation such as environmental loads, late and early fuel injection, piston ring wear, damaged fuel nozzle etc. One of these variables is hull fouling degree which is used for the research in this paper. The limitations of using simulated data for scientific research is the possible inaccuracy of the mathematical model used for simulator programming. This can only be validated using data from onboard measurements on actual vessels.

Figure 2. *RoPax Ship Model Particulars (ERS 5000 TechSim 2019)*

- Length, overall – 125 m
- Breadth, molded – 23.4 m
- Designed draft, molded – 5.3 m
- Service speed – approx. 19 knots

Propulsion:
- 2 x MAN 8L32/40 Four stroke, medium speed, turbocharged, non-reversible main diesel engine, MCR 4,000 kW at 750 RPM
- 2 x Controllable Pitch Propeller (CPP)
- CPP Bow Thruster 1000 kW
- 2 x Fin Stabilizers

Electric Plant:
- 3 x Diesel Generator 600 kW, 450V AC, 60 Hz, 3 ph (diesel engine – CAT 3508B)
- 1 x Shaft Generator (PTO) 1160 kW, 450V AC, 60 Hz
- Emergency Diesel Generator 260 kW, 450V AC, 60 Hz

Area of navigation chosen for the simulations is the Adriatic Sea, however since environmental loads i.e., wind, waves, wave spectrum and sea current, were not simulated for the purposes of this research the area of navigation is of little importance and of no impact. The speed parameter, therefore, can be viewed as both speed through water (STW) and speed over ground (SOG). Without environmental load variables the sea is perfectly calm and the simulated vessel is sailing in ideal conditions. Fuel used for the combustion process in the main engines is a distillate marine fuel mark “X” (DMX) with less than 0.1% of sulphur content. The simulated parameters recorded for the purpose of this research were vessel speed (STW/SOG) shown in knots (kn), shaft power shown in kilowatts (kW), specific fuel oil consumption (SFOC) shown in grams per kilowatt-hour (g/kWh), carbon dioxide emission (CO_2) shown in percentage by volume (%) and nitrogen oxides emission (NO_x) shown in parts per million (ppm). The degree of hull fouling was chosen based on experience in this field of research and was set at values expressed in percentage (%) as is shown in Table 1. The degree of hull fouling was changed at specific time intervals chosen to give the parameters recorded enough time to stabilise at a relatively constant value. The observed time needed for parameter stabilisation was two minutes.

Table 1. *Hull Fouling Degree Change Related to Specific Time Intervals*

T (min)	0:00	2:00	4:00	6:00	8:00	10:00	12:00
Hull fouling (%)	0	25	50	75	85	95	100

All of the above-mentioned parameters were simulated under two different engine loads. The engine loads simulated are 90% and 80% of maximum continuous rate (MCR). These engine loads were chosen based on usual optimum engine load for the specific engine type used in the referent vessel and to simulate two different regimes of navigation in order to analyse the impact of hull fouling in different navigational regimes (L+V32/40 Project Guide 2010).

Results and Discussion

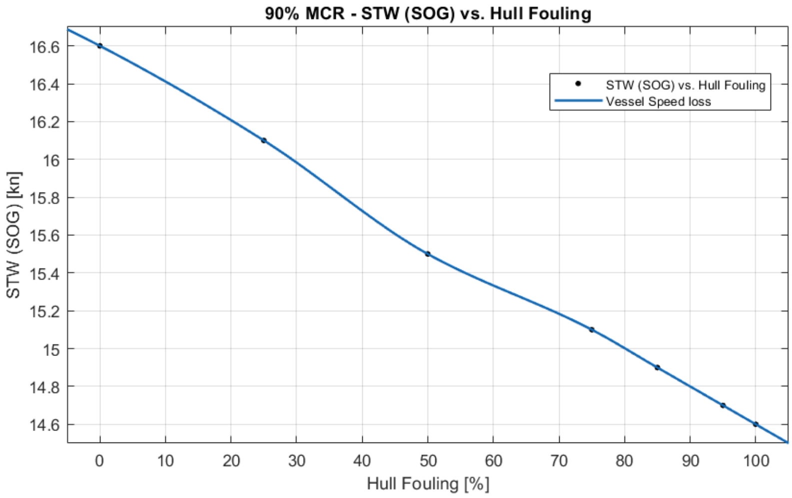
The purpose of this research was to gain insight about potential ship fuel consumption and emission increase due to a changing degree of hull fouling (HF) within the frame of conditions defined in the previous chapter. The results of the research are presented through various parameters (speed through water/over ground, shaft power, specific fuel oil consumption and CO_2/NO_X emissions). Two separate simulations were made based on two different navigational regimes (engine loads). The data accumulated for the 90% MCR engine load is shown in Table 2.

Table 2. *Effect of Hull Fouling at 90% MCR Engine Load Navigational Regime*

HF (%)	STW / SOG (kn)	Shaft Power (kW)	SFOC (g/kWh)	CO_2 (%)	NO_X (ppm)
0	16.60	2636	193.04	6.70	875.54
25	16.10	2666	193.04	6.70	885.70
50	15.50	2686	191.35	5.80	912.74
75	15.10	2700	191.35	5.80	917.08
85	14.90	2705	191.35	5.80	918.55
95	14.70	2710	191.35	5.80	919.98
100	14.60	2714	191.35	5.80	920.50

In the 90% MCR simulation, vessel speed reduction was analysed with respect to the reference vessel speed obtained in zero hull fouling value condition. The reference speed for this particular vessel was determined to be 16.60 kn under the 90% MCR engine load. Considering the ideal sea conditions with the only added resistance factor introduced in the form of steadily increasing hull fouling a significant speed loss occurs as is shown in Figure 3. The largest speed loss occurred in the transition between zero (0%) value hull fouling and 25% of hull fouling which amounts to 0.5 kn of speed loss. The second largest speed loss amounts to 0.4 kn and occurs in the transition between 50% and 75% of hull fouling. Vessel speed at the end of the simulation where hull fouling is at 100% value is 14.6 kn which indicates the total speed loss of 2.0 kn.

Figure 3. *Impact of Hull Fouling on Vessel Speed Loss at 90% MCR*



Continuing with the 90% MCR simulation, the shaft power has shown a steady but not a significant increase with every step of hull fouling degree rise. The reference shaft power for this analysis is 2636 kW at zero (0%) value of hull fouling while the maximum shaft power at 100% hull fouling value is 2714 kW which indicates an increase of 78 kW as is shown in Figure 4. Specific fuel oil consumption (SFOC) exhibits only one instance of change in value at the step between 25% and 50% of hull fouling value as is shown in Figure 5. This decrease of SFOC which equates to a drop from 193.04 g/kWh to 191.35 g/kWh can be attributed to an increase of turbocharger efficiency for this specific engine approximately at 2680 kW of shaft power.

Figure 4. *Impact of Hull Fouling on Shaft Power at 90% MCR*

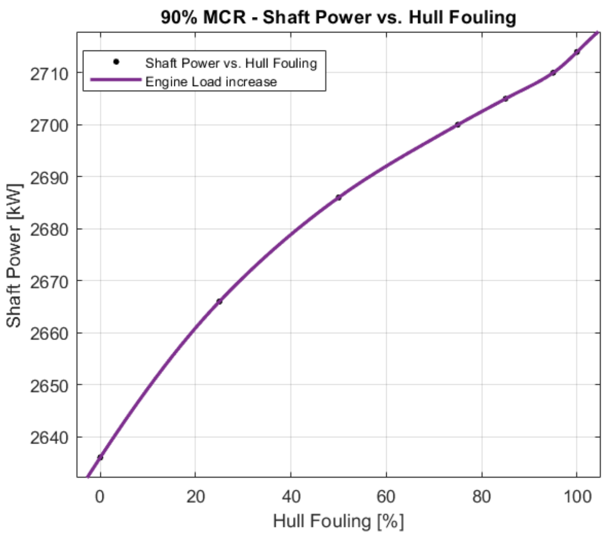
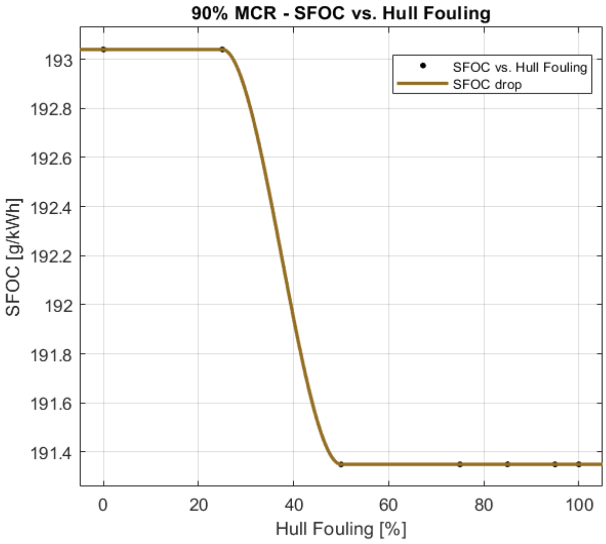


Figure 5. *Impact of Hull Fouling on SFOC at 90% MCR*



The last two parameters of the 90% MCR simulation are CO_2 and NO_X emissions for which the respective reference values, at zero (0%) hull fouling value, are 6.70% by volume of CO_2 and 875.54 ppm of NO_X. CO_2 exhibits a singular drop at the same point where SFOC decreases, as is shown in Figure 6, which is consistent with the increased turbocharger efficiency argument. On the other hand, NO_X shows a constant increase in value with every step of hull fouling value increase which can be attributed to higher maximum combustion temperatures which are a result of a consistently higher engine load indicated by the shaft power parameter. The impact of hull fouling on NO_X emission is shown in Figure 7.

Figure 6. *Impact of Hull Fouling on Carbon Dioxide Emission at 90 % MCR*

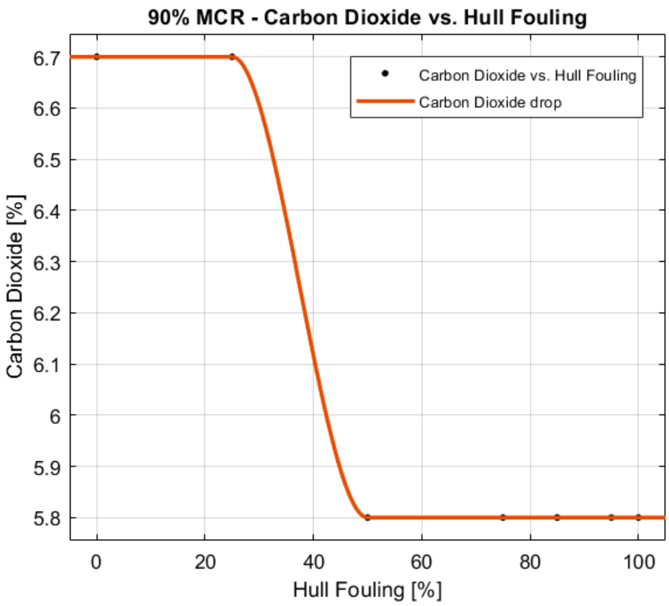
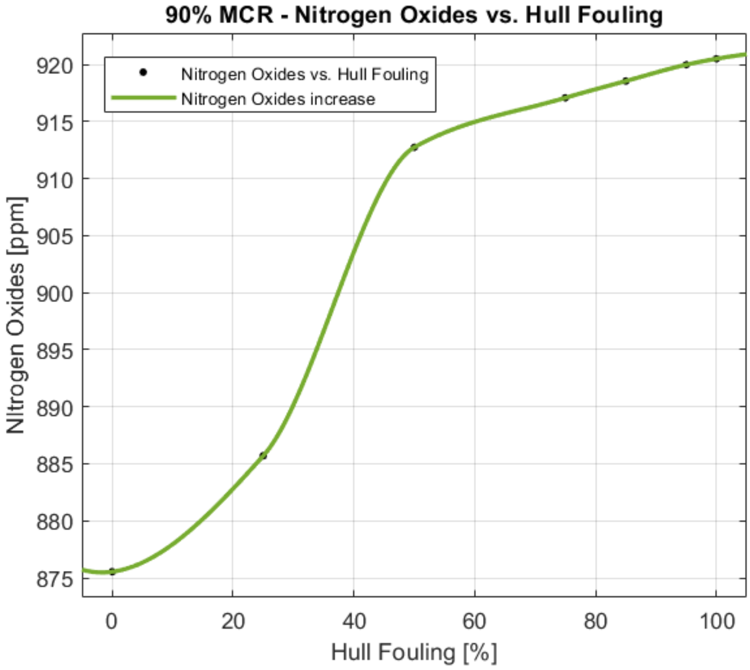


Figure 7. *Impact of Hull Fouling on MCR Nitrogen Oxides Emission at 90%*



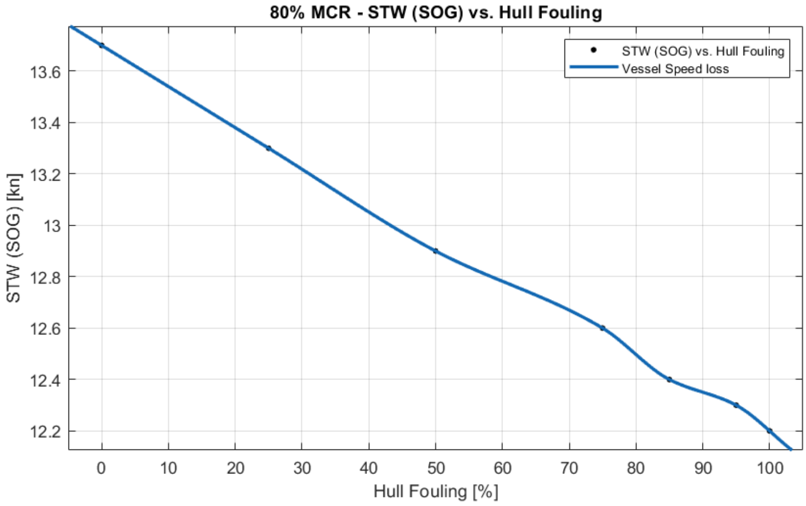
The second scenario simulated was at 80 % MCR engine load as stated in the text above. The data accumulated in this simulation is shown in Table 3.

Table 3. *Effect of Hull Fouling at 80% MCR Engine Load Navigational Regime*

HF (%)	STW / SOG (kn)	Shaft Power (kW)	SFOC (g/kWh)	CO_2 (%)	NO_X (ppm)
0	13.70	1768	196.35	6.30	678.61
25	13.30	1785	196.42	6.40	684.51
50	12.90	1801	196.42	6.40	689.51
75	12.60	1816	196.42	6.40	697.96
85	12.40	1824	196.42	6.40	699.98
95	12.30	1828	196.42	6.40	701.59
100	12.20	1832	196.42	6.40	702.81

The reference value of vessel speed is 13.7 kn at zero (0%) value of hull fouling. Speed loss is consistent with the increase of hull fouling degree, as is shown in Figure 8, and is significant like the speed loss in the first (90% MCR) simulation. However, the total speed loss is less than in the first scenario, and it equates to 1.5 kn with the lowest vessel speed being 12.2 kn at 100% hull fouling value.

Figure 8. *Impact of Hull Fouling on Vessel Speed Loss at 80% MCR*



Shaft power exhibits a consistent increase with the increase of hull fouling value with it being lesser than at 90% MCR load by approximately ~ 900 kW. The reference shaft power, at zero (0%) hull fouling value is 1768 kW. Maximum shaft power, at 100% hull fouling value, equates to 1832 kW exhibiting a total shaft power increase of 64 kW which is less than at the 90% MCR engine load scenario. Shaft power increase is shown in Figure 9.

However, SFOC is exhibiting different behaviour in this scenario than in the 90% MCR one, as shown in Figure 10. Instead of a decrease like in the first scenario, here there is a slight increase at the step between 0% and 25% hull fouling value and then a constant unchanging value until the end of the simulation equating to 196.42 g/kWh with the reference value of SFOC equating to 196.35 g/kWh. This indicates that there is a slight drop in the turbocharger efficiency for this type of engine before it starts increasing again which is also indicated by the value of CO_2 emission.

Figure 9. *Impact of Hull Fouling on Shaft Power at 80 % MCR*

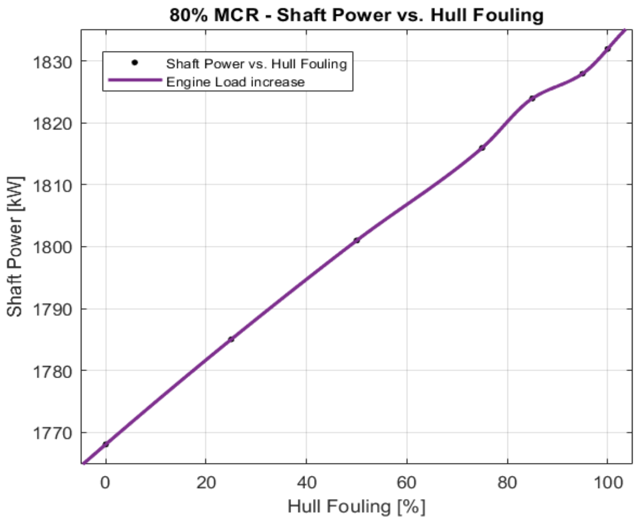
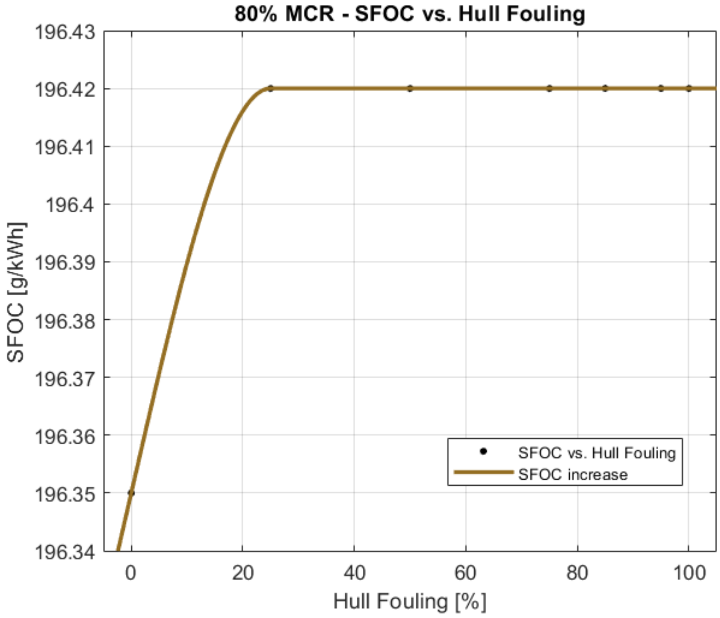


Figure 10. *Impact of Hull Fouling on SFOC at 80% MCR*



CO_2 reference value is 6.30% by volume. The only increase is at the same step as with the SFOC increase when hull fouling increases from 0% to 25% value, as shown in Figure 11. The increased value of CO_2 at that point equates to 6.40% by volume and stays constant until the end of the simulation. This complements the turbocharger efficiency discussion explained in the text above. Unlike SFOC and CO_2, NO_X is exhibiting the same constant increase in value with the increase of hull fouling and shaft power as in the first (90% MCR) scenario. This is consistent with the argument of increased engine load and maximum combustion temperatures in the cylinders of the main engine. NO_X increase is shown in Figure 12.

Figure 11. *Impact of Hull Fouling on Carbon Dioxide Emission at 80% MCR*

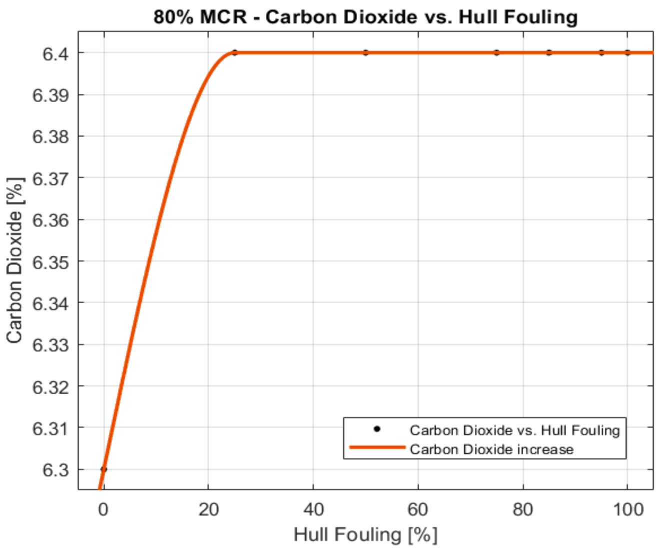
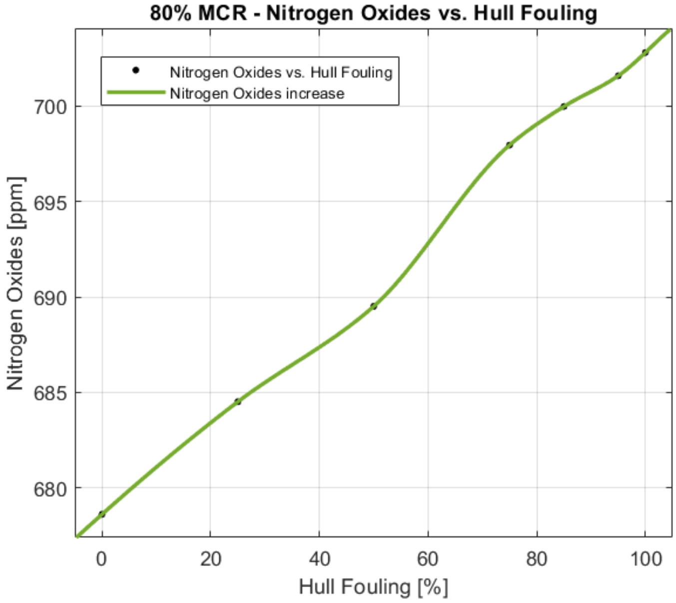


Figure 12. *Impact of Hull Fouling on Nitrogen Oxides Emission at 80% MCR*



Of all the above analysed parameters the largest impact of hull fouling was on vessel speed loss at the 90% MCR engine load scenario and thus this parameter was chosen for the calculation in the example presented in the following text.

The following calculation will exhibit the effect of vessel speed loss due to full fouling on fuel consumption and emissions on an actual RoPax ferry route between Italy and Croatia. The ferry route chosen for the example is Zadar – Ancona with the length of 102 NM (nautical miles), shown in Figure 13. The parameters used for the calculation are from two hull fouling steps from the 90% MCR scenario and are as follows:

- zero value hull fouling with the reference vessel speed of 16.6 kn and
- 95% hull fouling value with the vessel speed of 14.7 kn.

Figure 13. *Zadar – Ancona Ferry Route (Pavin 2021)*

The recorded value of specific fuel oil consumption for zero value hull fouling equates to $SFOC = 193.04\ g/kWh$ while the value of specific fuel oil consumption for 95% hull fouling equates to $SFOC = 191.35\ g/kWh$. Shaft power for zero value hull fouling equates to $P = 2636\ kW$ while the value of shaft power for 95% hull fouling equates to $P = 2710\ kW$.

To calculate fuel consumption expressed in mass per unit of time the following formula was used:

$$FC = \frac{SFOC \cdot P}{1000} \qquad (1)$$

where FC is fuel consumption expressed in mass per unit of time (kg/h), *SFOC* (g/kWh), and *P* is shaft power (kW).

The fuel consumption calculated for the 0% hull fouling voyage equates to $FC_0 = 508.85\ kg/h$ while the fuel consumption calculated for the 95% hull fouling voyage equates to $FC_{95} = 518.56\ kg/h$.

Due to the occurring vessel speed loss the time of voyage will differ and thus needs to be calculated and introduced into the total calculation. In order to calculate the voyage time between the ferry ports of Zadar and Ancona the following formula was used:

$$t = \frac{s}{v} \qquad (2)$$

where *t* represents voyage time (h), *S* represents voyage lenght (NM), a *V* represents vessel speed (kn).

The calculated voyage time for the 0% hull fouling scenario equates to $t_0 = 6.15\ h$ (6 hours 9 minutes) while the voyage time for the 95% hull fouling scenario equates to $t_{95} = 6.94\ h$ (6 hours 56 minutes) indicating that the 95% hull fouling voyage is 47 minutes longer.

By multiplying voyage time (t) with fuel consumption (FC) the total fuel consumption for each voyage is calculated. The total fuel consumption for the 0% hull fouling voyage equates to $FC_{0,TOT} = 3129.43\ kg$ while the total fuel consumption for the 95% hull fouling voyage equates to $FC_{95,TOT} = 3598.81\ kg$. This calculation shows a significant increase of total fuel consumption due to increased hull fouling. The total fuel consumption is higher in the 95% hull fouling scenario by 469.38 kg of fuel or by ~ 15%. The increased fuel consumption per voyage indicates a significant increase in CO_2 and NO_X emissions as well.

Conclusion

The results of this research were effective at proving that increased hull fouling leads to increased fuel consumption and by extension to increased exhaust gas emissions. Considering that the prevalent fuels used in maritime transportation are still fossil fuels this leads to increased greenhouse gas and pollutant emissions. The results have also shown that voyage delay and energy efficiency are impacted by the degree of fouling. The example shown in the text above indicates how significant the impact of a ship's hull fouling is on voyage time and fuel consumption, thus if daily fuel oil consumption in that scenario is multiplied by ongoing fuel oil price it leads to high financial costs. The improved propulsion efficiency and reduced daily fuel consumption could be achieved by periodic hull cleaning and adequate dry-docking. Moreover, the optimal frequency of hull maintenance could be selected depending on differences in fuel consumption. The data in this research can be used to further analyse the maritime vessel exploitation economy and to improve hull maintenance strategies.

References

Dere C, Deniz C, Zincir B, Kandemir C (2016) Hull fouling effect on propulsion system components. In *The Second Global Conference on Innovation in Marine Technology and the Future of Maritime Transportation*, 24-25 October 2016, Bodrum, Muğla, Turkey.

ERS 5000 TechSim (2019) *MAN Diesel 32/40 twin medium speed engine + CPP - RoPax ferry, commercial specification version 1.7.244.0*. Wärtsilä Voyage Limited.

Giorgiutti Y, et al. (2014) Impact of fouling on vessel's energy efficiency. In *25º Congresso Nacional de Transporte Aquaviário, Construção Naval e Offshore*, Rio de Janeiro.

L+V32/40 Project Guide (2010) *Marine Four-stroke diesel engines compliant with IMO Tier II, MAN Diesel & Turbo*. Augsburg, Germany.

Munk T (2006) Fuel conservation through managing hull resistance. In *Motorship Propulsion Conference*, 26 April 2006, Copenhagen.

Oliveira DR, Granhag L (2020) Ship hull in-water cleaning and its effects on fouling-control coatings. *Biofouling* 36(3): 332–350.

Orović J, Valčić M, Knežević V, Pavin Z (2022) Comparison of the on board measured and simulated exhaust gas emissions on the ro-pax vessels. *Atmosphere* 13(May): 794.

Pavin Z (2021) *Impact of environmental loads on ship speed*. Master Thesis. Rijeka: Faculty of Maritime Studies, University of Rijeka.

Resolution MEPC.207(62) *Annex 26 – 2011 guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species*.

Tarelko W (2014) The effect of hull biofouling on parameters characterising ship propulsion system efficiency. *Polish Maritime Research* 21(4): 27–34.