USING A TAILORED SYSTEMS ENGINEERING PROCESS WITHIN CAPSTONE DESIGN PROJECTS TO DEVELOP PROGRAM OUTCOMES IN STUDENTS

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Abstract – With the shift towards outcomes based accreditation, it is imperative that engineering courses develop their outcomes within students, and not just assess if students possess them. Many attempts have been made to integrate this development within capstone design projects with varying degrees of success. It was found that using a tailored systems engineering process increased the possibility that students developed desired outcomes within their design experience. A set of hybrid attributes was developed by comparing and mapping the ABET program outcomes and the Institution of Engineers Australia’s graduate attributes. The tailored systems engineering process was then compared to each hybrid attribute to determine how the process developed that attribute within students.


INTRODUCTION

The introduction of outcomes based accreditation systems, both in Australia and the United States, has lead to a significant amount of work trying to understand how to develop and assess these outcomes in students [1]. In Australia, the Institution of Engineers Australia (IEAust) have developed a set of “graduate attributes” that are used to accredit graduate engineers the same way that the Accreditation Board for Engineering and Technology’s EC2000 program outcomes do in the United States [2] [3]. The ABET and IEAust outcomes are very similar allowing outcome development systems and methods to be shared between Australian and US institutions.

This paper discusses the development of these outcomes in students within a capstone design course. Tooley and Hall [4] illustrated that “Capstone design courses are one of the most effective ways for engineering departments to facilitate the outcomes described by ABET Criterion 3”. In particular, the use of a tailored systems engineering process (TSEP), developed by the authors [5], within capstone design courses to develop these outcomes is discussed. The discussed TSEP provides a framework for the design process, as well as for developing certain program outcomes within the students involved. The paper presents each common theme of the IEAust and the ABET systems and explains how the TSEP develops that attribute in students.

PROGRAM OUTCOMES AND GRADUATE ATTRIBUTES

The Institution of Engineers Australia is the major accrediting body for engineers in Australia and has been a signatory to the Washington Accord since it was first signed in 1989 [6]. The Washington Accord recognises the equivalence of engineering programs in several countries, including Australia, New Zealand, the United Kingdom and the United States. After a major review of Australian engineering education, the ensuing report [7] advocated fundamental changes in engineering education, that paralleled “those of similar reviews undertaken in other countries around the world since the early 1990’s” [2].

One of the outcomes of this report was the shift in the accreditation of programs and students to using graduate attributes. This paralleled closely ABET’s move toward program outcomes. These graduate attributes are aimed to “ensure that graduates from an accredited program are adequately prepared to enter and to continue the practice of engineering” [2]. They come from an understanding that new graduates need knowledge and skills that they have not needed in the past, particularly in areas of multi-disciplinary teamwork and communication, as well as having an understanding of the global scope of engineering, ethical responsibilities and sustainability.

The graduate attributes introduced by the IEAust are similar to the program outcomes introduced by ABET [3] as program outcomes. For the purposes of this paper, we wish to examine common outcomes from both sets, and look at how the tailored systems engineering process can be used to develop these general outcomes. The Institution of Engineers Australia’s graduate attributes are presented here for reference as some readers may not be as familiar with them as the ABET program outcomes. The IEAust graduate attributes are [2]:

i) Ability to apply knowledge of basic science and engineering fundamentals;
ii) Ability to communicate effectively, not only with engineers but also with the community at large;
iii) In-depth technical competence in at least one engineering discipline;

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iv) Ability to undertake problem identification, formulation and solution;
v) Ability to utilise a systems approach to design and operational performance;
vi) Ability to function effectively as an individual and in multi-disciplinary and multi-cultural teams, with the capacity to be a leader or manager as well as an effective team member;

From these two lists of outcomes, it is possible to match similar words that seem to indicate at face value that common themes exist between the two sets. For instance, ABET outcome f, which is concerned about professional and ethical responsibility seems to have a common theme with the IEAust graduate attribute ix, which talks about an understanding of professional and ethical responsibilities. While the actual implementations may be different, this comparison seems to suggest that some common themes can be extracted from the two sets. These “hybrid attributes” are presented in Table I.

### Table I

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<tr>
<th>Hybrid Attribute</th>
<th>IEAust Graduate Attribute</th>
<th>ABET Program Outcome</th>
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<td>Application of basic science and engineering</td>
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<td>Communication skills</td>
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<td>In-depth technical competence</td>
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<td>Teamwork</td>
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<td>Social, cultural, global &amp; environmental awareness</td>
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<td>Lifelong learning</td>
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The tailored systems engineering process that can be used in a capstone design project was initially developed by the authors to raise the level of professionalism in undergraduate student projects. It was also aimed at helping the students using the process to develop some of the graduate attributes specified by the IEAust.

The tailored systems engineering process itself is based on the IEEE-1220 standard [8] for the management of the systems engineering process. This standard was chosen because it not only considers the process as a whole, but it sets out what each step entails logically. The standard is intended for commercial use and is designed to be tailored with specific projects in mind. Finally, it is easily available and relatively straightforward to use and implement.

The process was tailored iteratively as part of a case study in an undergraduate robotics project at the University of Queensland. Initially the IEEE-1220 standard was used directly by the project members, along with a set of developed tools. It was found that this method did not work, as the full systems engineering process was too complicated in its original form to be used by undergraduates [5].

After a review of this first application, it was determined that the process would need to be tailored in order to be used by undergraduates. The real question was, what level of tailoring was required so that the final process was easy to use, but did not lose the essence of systems engineering? How much tailoring should take place from the original process? If the level was too high, then too much would be removed or changed, resulting in a process that did not really embody the heart of systems engineering. If however the level of tailoring was too low, then the process could be left too complicated and hard to use, as the results from the first application of the full process point to. It was determined that the level of tailoring should be such that an undergraduate with some knowledge of systems engineering and its benefits would not be able to tell the difference between a product developed using the full process and one developed using the tailored process. If there was no

Analyse and interpret data. Possible reasons for this are beyond the scope of this paper. The other point of interest is the pseudo-linkage of the ABET program outcome k to the IEAust graduate attribute iii. The ABET outcome is not explicitly about in depth knowledge in one or more areas, as the IEAust attribute is, but in order to use the techniques, skills, and modern engineering tools necessary for engineering practice outcome k, some in depth knowledge would be required.

The themes presented in Table I are then the hybrid outcomes that will be used in this paper to look at how the tailored systems engineering process developed by the authors [5] used in a capstone design project can have the potential to develop these outcomes within the students involved.
appreciable difference, then tailoring was successful. Appreciable difference meant that the products met the same initial requirements and had the same thorough processes in their development, even if the physical realisations were different.

The tailored systems engineering process that was developed was modified extensively from the original IEEE-1220 standard by combining some sections and removing others. All of the sections were reworded in student “friendly” language that explains exactly what is required and what must be done. Some sections were added to make the process “user friendly” as possible and to get the maximum benefit out of the process for the project concerned, such as an initial inputs section and a project makeup section. The tailoring process reduced 76 pages into 20, customised specifically for students to use within undergraduate projects.

**Implementation of Tailored Process**

Once created, the tailored systems engineering process was then used within the undergraduate robotics project to develop a set of robots to compete in a robotics competition in Japan. The implementation of the TSEP involved the project members following the steps outlined in the tailored process in a traditional, pens and paper way. Each section was examined and followed by the group in a linear manner.

While initially some explanation was required about how to actually use the process, the steps to take, once the team began they followed the process easily. The team members commented that they could understand most of what the process was asking them to do. Some parts though were still a bit too complicated and the group members could not understand how they fit in with the overall process.

The final robot that was developed by the team was of a much higher quality than robots that had been developed in the past without the TSEP. This was both the feeling of the team members and the author. The final product met the initial requirements, which had not occurred in the past to a certain extent. The team also felt that the process they used to develop the robot helped them understand not only how to apply a systems approach to design, but also helped them manage their time and resources. This was because they could see clearly what steps they had accomplished and what was yet to come. The process also helped meet specified target goals and reviews on time, which was unheard of in the project in the past.

The products produced and the feedback from the team members seemed to indicate that the process was working. It was of benefit to the students and it was producing a better quality product, compared to previous years. One of the major strengths of the TSEP that was pointed out by the team was that it was easy to follow. You could do it section by section and not get caught up with what you have to do in the future. In the previous design methodology, there was a lot of jumping ahead and backtracking, leading to confusion on the part of the team members.

One of the obvious weaknesses of the tailored systems engineering process, besides some sections still being perceived as too complicated was its actual implementation. The group members felt that all though they could use the process, it could be made much easier to use and handle. It could also be made easier to manage, as the current system generated a large paper trail. Various methods of implementation were advanced by the group members, including a computer based program that could be extended to a web-based program.

Given that the TSEP seems to work at some level and offers real benefit to the students that use the process, how can these results be applied to other areas? One obvious area that the tailored systems engineering process can be applied to is within capstone design courses. While the process was developed in an extra-curricular environment, it is general enough to be applied within capstone design projects. One obvious question is why? What is different about the tailored systems engineering process from traditional capstone design processes? While these traditional processes can be a very broad spectrum of possibilities, there are a few points that are different.

Firstly, the TSEP emphasises process, the process that students go about developing a system. Rather than just coming up with something that works, the tailored process steps the students through what they have to do, starting from the requirements, functions then to a solution. While some courses do embody systems engineering, they usually have at their heart only the vague concepts of systems engineering, rather than a descriptive process. The tailored systems engineering process can be used directly, or can form the backdrop, so that lecturers have somewhere to point students who want to know more about the process without having to go to a full standard.

Secondly, it is tailored with the students learning in mind. It was developed to help students learn about systems engineering, as well as developing other skills and attributes. This is something that most traditional process do not have built into them. This is especially important when trying to develop in students ABET c or IEAust graduate attribute v. A more comprehensive explanation of how the tailored systems engineering process can develop the various hybrid attributes in students can be found in the systems engineering in capstone design section.

**Outcome Development in Capstone Design**

In 1995, a study was conducted into capstone engineering courses throughout North America [9]. The study found that “many engineering programs were using senior design/capstone-type courses to help prepare students for engineering practice” [10]. While this survey was conducted pre-ABET, it points to the fact that many people had already
been using capstone design projects to prepare engineers for real world professional practice [4] [11] [12].

With the inception of the ABET program outcomes in the US and the IEAust graduate attributes in Australia, capstone design projects became a obvious vessel for possible development and assessment of these outcomes within students [4] [10] [13].

More research and development seems to have been in the area of the assessment of these outcomes, rather than the development of them within students. Felder and Brent [1] try to explain this inconsistency; “The tacit assumption seems to be that determining whether or not students have specific skills is much harder than equipping them with those skills [where] the opposite is closer to the truth” [1]. There have been many attempts at trying to develop program outcomes within students involved in capstone projects with an emphasis on trying to develop those outcomes that are not purely technical [11] [12] [13].

While this is certainly not an exhaustive list of examples of trying to develop program outcomes in students within a capstone framework, the examples do illustrate that many feel that it is possible. Whether or not these attempts do actually develop these outcomes within students is beyond the scope of this paper. What then does the tailored systems engineering process have to offer to improve this development?

SYSTEMS ENGINEERING IN CAPSTONE DESIGN

The TSEP when applied within a capstone design project has a greater potential to develop program outcomes within students compared to traditional capstone projects. The TSEP provides an engineering framework for the design process, as well as alerting the students using the process to other issues, such as the social and environmental impacts of possible designs. It allows the development of their communication and teamwork skills far more due to the nature of the process. This section presents each hybrid attribute and explains how the tailored systems engineering process can help to develop that theme within students.

Application of Basic Science and Engineering

"An ability to apply knowledge of mathematics, science, and engineering is inherent to capstone design courses” [4]. In order to perform design calculations, trade off studies, and develop basic systems, knowledge of these areas is essential. If this knowledge needs to be developed to a greater extent within students, then it is done so in order to solve a problem, which has been proven to be more beneficial in developing and instilling knowledge in students than lecturing to them [14].

Tooley and Hall [4] also point out that an important application of basic engineering knowledge is in project management. Using the tailored systems engineering process, this is developed to a greater extent because the tools and framework within the TSEP for the management of the project are much more rigorous than without some sort of systems engineering process.

Communication Skills

Using the TSEP, the students not only have the standard communication exposure in capstone design projects, such as reports, oral presentations and workbooks, but also have to communicate with the customer to develop the initial customer requirements. This step is an essential part of systems engineering and the tailored process help students develop communication skills with other stakeholders who are usually not sure what they actually want the product to do. These communication skills are aligned with the sorts of skills that students will require when they graduate and enter professional practice.

In-Depth Technical Competence

While the groups using the TSEP in capstone design projects are multidisciplinary, each individual member will have a certain role that will depend on their in-depth knowledge. For instance, a design team for a robot may be made up of mechanical engineers, electrical engineers, computer engineers, software engineers and mechatronics engineers, that may have to work with people from other disciplines such as business/marketing, economics and even social science. The design will enable them to develop their knowledge and competence in that field by applying what they had learnt in other courses in a real life situation. Anything that the students do not know, the will have to research and figure out for themselves, further developing their in-depth knowledge.

This theme also encompasses ABET’s outcome k, as each team member will have the chance to use and develop abilities with techniques, skills and engineering tools specific to their discipline. Using the TSEP, CAD and CAM tools, project management tools, finite element analysis tools and a number of other modern engineering tools are used within real world projects, so that the students gain an understanding of what professional practice could be like.

Problem Identification, Formulation and Solution

In a capstone design course, the ability to identify problems and formulate solutions is an essential skill that students will develop with experience. In any design, the major problem identification is the initial motivation for the design. The TSEP, through design verification and validation, brainstorming and trade off studies, offer students many opportunities to develop problem-solving skills. The students are required to gather information to solve the various problems, another useful skill that they can develop for professional practice.
Design and Conduct Experiments

In order to conduct trade of studies within the TSEP, data may need to be gathered about the various alternatives. This data would be gathered in the form of experiments, with the students having to design the experiments based on what they are trying to find, conduct the experiments, then analyse the results to feed information back to the decision making process.

Another useful tool within the TSEP is the ability to prototype possible systems solutions. This prototyping is a form of experimentation, where students build prototypes to answer particular questions regarding aspects of the solution. The prototypes are analysed to feed information back to the design.

Systems Approach to Design

The tailored systems engineering process makes the students take a systems approach to the design of the product, including life cycle analysis, requirements analysis and verification/ validation issues. The students involved are able to develop a systems approach to design through the repetitive use of the process, again an application of problem based learning (PBL) [14]. This occurs much more than in traditional capstone courses as there is an actual process at its heart. Traditional capstone courses usually present systems engineering as a few ideas, where as the TSEP presents for the students a full process that they can use. It has also been designed to have the students learning in mind, teaching them about systems engineering and a systems approach to design.

Teamwork

Teamwork is an essential part of design work and for using the TSEP. The design teams using the systems engineering process are mainly multi-disciplinary teams due to the nature of the problem. The members of the team are able to develop teamwork skills in order to produce a coherent final product. They learn to use each other’s strengths and weaknesses to perform the tasks of the TSEP. The TSEP also emphasises the various members’ roles and responsibilities much more than traditional processes. As such, everyone needs to work together in their role to get the job accomplished. This emphasis on teamwork, which certainly exists in traditional capstone courses, is essential for the use of the TSEP. The students soon realise this, which adds motivation to lean ideas such as negotiation, a critical component of communication.

Social, Cultural, Global & Environmental Awareness

This outcome can best be developed using the tailored systems engineering project through the choice of a suitable project. If the project comes from a community need, then the students would be able to develop a social and cultural awareness. If then the project also had some environmental issues, then the students could develop environmental awareness. An understanding of the global nature of engineering could be accomplished by looking at how other groups around the world are solving the same sorts of problems, and what techniques they are using.

Sustainability

Sustainability is a contemporary issue that engineers have to be aware of in the current global engineering profession. Choosing a project that considers the sustainability of X within the overall project can best develop the theme of sustainability within students. The TSEP supports this consideration and emphasises the various decisions that can be made to come up with a final solution, only some of which are sustainable.

Professional and Ethical Responsibilities

“Capstone design courses offer a unique opportunity to learn about ethics in a realistic context” [4]. Again the choice of project is critical, and can closely tie in with the issues of society, culture and environmental awareness. The TSEP can be used to introduce ethical issues with possible systems solutions, ethical concerns that the customer may have and the use of intellectual property (IP).

Lifelong Learning

Lifelong learning is an essential skill for engineers to possess and in the context of a capstone design project, almost impossible not to develop. Because of the nature of design projects, students will not have all the necessary knowledge that they will require to find a solution. They will have to research particular topics, learn how to use certain tools and overall, learn about the tailored systems engineering process. When the students realise that they have to reach outside of their experiences constantly in the design process, they are on their way to developing lifelong learning skills.

Conclusion

This paper looked at the development of program outcomes in students within capstone design projects. In particular, it looked at how a tailored systems engineering process can improve the chance of the students developing outcomes within them, compared with traditional capstone courses. There is a great need at the moment to ensure that courses are developed that aim to develop outcomes in students, rather than just assess them. Capstone design projects offer a perfect vessel for the development of these outcomes in students, but it should be noted that just because students take part in capstone design courses doesn’t necessarily mean that they will develop outcomes, only that the possibility is there for them to. The TSEP increases this possibility but again, does not directly mean that they will.
The results of the implementation of the tailored systems engineering process seem to indicate that a group of undergraduate students are able to apply a formal process in their design activities. This was tested in an extracurricular environment but the results can be used for curricular projects as well. The students involved were able to follow the process well, and all felt that they learnt more about systems engineering through applying this process than they would have though the more traditional lecture based methodologies. While the students did make mistakes along the way, they used the experience to learn even more about not only systems engineering but other graduate attributes.

This paper also suggests that outcomes are best developed within an integrated setting, rather than singling out one particular attribute for one project. While the students involved in the robotics project were primarily developing an understanding of systems engineering, they would not have been able to develop that attribute if they were not developing other attributes, such as communication, teamwork, problem solving and many more. This is an interesting result in the wider context, especially with the shift towards trying to develop and assess the ABET outcomes and IEAust attributes in students.

Future work in this area would include the refinement of the tailored systems engineering process in response to the weaknesses identified. It would also include conducting a critical analysis of other systems engineering based processes that are aimed at educating students. In particular, looking at what computer and web-based tools have been developed in the past, in order to develop a useful tool to use the TSEP. Another would be testing the TSEP within various curriculum courses at various year levels, to see if the results obtained in this study can be extended. A finally future goal would be trying to actually assess if students have developed the program outcomes after using the tailored systems engineering process.

REFERENCES


