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THE DEVELOPMENT OF A TAILORED SYSTEMS ENGINEERING PROCESS FOR EXTRACURRICULAR STUDENT DESIGN PROJECTS

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Abstract

A tailored systems engineering process was developed for undergraduate projects to help students learn about systems engineering while at the same time, delivering a level of professionalism to the projects concerned. Initial attempts at applying the full systems engineering process to an undergraduate project were unsuccessful, as the full process was too complicated for the students involved to use and understand. Subsequently, a systematic approach was used to create the tailored systems engineering process. This process was then applied successfully in an undergraduate project to produce a product that was of a comparable standard to one developed with the full process. The results of this study found that tailoring was necessary, that both the project and the students ultimately benefited from the application of the process, developing skills and abilities beyond those developed in traditional lectures. Some of the other lessons learnt about the tailoring process are also discussed, along with the future directions of this study.

Keywords: Systems engineering, experiential learning, engineering process, curriculum

1. Introduction

This paper presents the tailoring of a systems engineering process to be used specifically within undergraduate projects. The study came about because of a need to bring a degree of professionalism to student projects. It was also aimed at helping students develop broader graduate attributes specified by the Institution of Engineers Australia (IEAust) [1] and required by the University of Queensland.

Both industry and the profession are requiring graduates to have these skills and many more to augment the student's technical skills. Engineering graduates are expected to be able to work in and lead teams, take a systems approach to design and operations, be proficient communicators, be oriented towards sustainability, and to be life-long learners [1]. A recent survey of major engineering employers found that *"more than 97% of respondents concluded that their current engineers did not have the necessary skills or experience to carry out their duties to an acceptable level of competence"* [2]. Systems engineering offers a means to integrate the technical and the broader graduate attributes into engineering programs.

This paper presents a method of introducing systems engineering into engineering programs in the context of extracurricular design-construct-compete projects. This approach is a form of project based learning (PBL), where the guiding process for the students is provided by a systems engineering framework. This is somewhat different from the traditional problem based learning methodology. Project based learning has been accepted to provide a more favourable learning environment compared to traditional forms of education especially in terms of student motivation [3] [4] [5]. However, there is often a lack of a coherent engineering approach and as a result, most projects "run out of time", "produce junk" or produce "a semi-finished product" [3]. To overcome some of these shortcomings, project based learning needs to go hand in hand with a professional design approach. One such is the systems engineering process (SEP). This has been done to a limited extent [6] but not using a full system engineering framework.

The case study reported in this paper addressed the following questions;

1. Is the full SEP too complicated and bureaucratic to be applied ‘as is’ to undergraduate projects, or is tailoring going to omit too much essential information?
2. What sort of a SEP is required to maximise the benefit for the project, without overcommitting it to useless managerial and organisational hassles?
3. How should the tailoring process be undertaken? What conditions determine how much tailoring should take place?
4. Do both the project and the student ultimately benefit from the tailored systems engineering approach?
5. What lessons are there about the tailoring of the systems engineering process that can be applied elsewhere?

2. Systems engineering and the nature of undergraduate projects

2.1 Systems engineering

Systems engineering, while originating within the defence industry, has now spread to virtually every major engineering industry, including aerospace, transport and process engineering. It is an interdisciplinary management approach to the development of a product from a set of initial customer requirements. It focuses on the entire life cycle of a product, including development, manufacture, testing, transport, maintenance, training and disposal. It is concerned with the development of systems, from simple to very complex, with a focus on the entire life cycle of the system. Systems engineering also provides a management framework for the development to take place. It differs from integrated product development (IPD) as IPD is focused on the development of an individual product or a technology platform to develop a range of products [7] [8]. IPD usually develops less complex products with particular attention paid to development and production.

The systems engineering process is an ordered approach that converts a set of customer requirements into a final product. It has three main phases, requirements analysis, functional analysis and design synthesis, all balanced by systems analysis and control processes. It can be applied on many levels, depending on the complexity of the product. As such, it is suited to any undergraduate project, as it can go into as much or as little detail as is required, i.e. system, sub-system, component and so on.

The IEEE-1220 standard [9] was selected as the systems engineering framework for the case study reported in this paper. This standard was chosen over others because it not only considers the enterprise as a whole, but it also details the steps involved in each section of the systems engineering process. It is aimed at commercial use and is designed to be tailored to suit the needs of particular projects, including industrial projects. It is easily available and is relatively easy to use.

2.2 Undergraduate projects

Within most current engineering education programs, there are few opportunities for students to obtain a professional engineering experience. There is, however, an alternative to adding more project based subjects to an already full engineering program. This is through the use of undergraduate run, extracurricular projects. In the past, most of these undergraduate projects have offered students the opportunity to apply their engineering knowledge and to develop skills beyond those gained in their standard program. While this paper focuses on extracurricular projects, the principles can equally be applied to projects within the curriculum.

The projects considered in this study all had the following similarities.

- The projects have a volunteer workforce. The students receive no monetary benefits or academic credit for their work. They are under no obligation to participate. They do so to have fun, meet new people and obtain hands on experience.
- These projects run all year and across years, so that the learning cycle is a continual one. Students that join the projects in their first or second year can be involved until they graduate.
- They have a limited budget that is raised by the project members through sponsorship. There is no annual fixed budget, no reserves if the project runs out of time or money. This encourages the project to keep its own accounts and manage its time, adding to the multi-disciplinary environment.
- The projects are aimed at producing a real working product. This product may take many different forms; robots, racing cars and satellites just to name a few. These products though are either produced for a competition, as a research platform or aimed at a specific industrial need. They all must fulfil a set of requirements and are a one-off prototype or product.

The main undergraduate project used to formulate the tailored systems engineering process was RobotronicsUQ, a robotics team at the University of Queensland set up to compete in the international Robocon competition. Robocon, originally based in Japan, is now open to teams from universities and industry from across the Asia-Pacific. This competition has a different scenario and set of rules each year, and this means a new set of machines must be conceived, built and tested annually. Each competition usually involves a human powered machine and an autonomous machine working in tandem and these typically involve a complex mechanical mechanism. RobotronicsUQ is a multi-disciplinary team, made up of electrical, computer systems, software, mechanical and mechanical and space engineers. They are all undergraduate engineers and are part of the team to learn new skills and have some fun.

When the RobotronicsUQ team began competing in 1999, it wasn't as successful as it would have liked. After trying and dismissing the excuses of people, money and time, it was realised that they way forward was with a more professional attitude in both the management of the team and in the design and manufacture of the robots. A systems engineering framework was chosen as the basis of this paradigm shift as it offered help with not only the design and manufacture of the robots, but also allowed the team to deal with other life cycle related issues, such as the transportation of the robots. A systems engineering approach also offered a greater emphasis on the final product meeting its initial requirements.

3. Methodology

3.1 The first attempt

The initial attempt to introduce systems engineering to RobotronicsUQ involved the direct application of a set of tools based on IEEE-1220 standard [9]. These tools were in the form of question and answer papers, with the members filling out the various sections in response to questions. Rather than developing the entire set of tools at once, they were developed incrementally and tested on the members of RobotronicsUQ.

It was clear from the first explanatory session that this attempt was not going to work in its original form. While the tools were aimed at simplifying the systems engineering process, the team saw them as foreboding and a lot of work. They viewed the entire process as an added complication and couldn't immediately see a benefit in using the systems engineering process. It was soon realised that the tools and the entire process was too long to be used in an undergraduate environment. There was a lack of understanding of what a systems engineering process could do for the project. As a result, the members of the team were discouraged as the entire process lacked focus and direction.

3.2 Initial results

From this initial attempt, the following issues were realised as imperative to successfully integrate a systems engineering process into an undergraduate project.

- Present an overview of the systems engineering process first, detailing what occurs in each section
- Ensure that the benefits of the systems engineering process are made clear at an initial stage in order to encourage the team members to actively use the process
- Only keep the parts of the process that are essential to producing a successful product, and remove anything that is not absolutely necessary
- Develop a lead in section to help the students understand about the specifics of the project that they are in and to start thinking in a manner that will help them with the use of the systems engineering process
- Make the systems engineering process as user friendly as possible, including methods to make it easy to use and apply to undergraduate projects,

In order to accommodate the above principles, a tailored process was required. This process needed to be tailored so that it was easy for the project members to use and understand, but at the same time, still delivered a systems engineering framework that would benefit the project.

3.3 A systematic approach

In order to develop the tailored systems engineering process, a case study of RobotronicsUQ was conducted, which used the initial results stated in section 3.2 as a starting point. The research methodology used in this case study was put forward by Yin [10] and was used to develop, verify and test the final tailored process. A case study methodology was chosen above other research methods as it allowed the process to be changed as interim results were obtained.

The purpose of the case study was two fold.

1. To determine if a tailored systems engineering process was required and if the project and the student ultimately benefit from its implementation
2. To develop the optimal tailored systems engineering process for both the student's learning and the project's success

In order to accomplish the first task, a tailored systems engineering process was developed and tested. The outcomes from the projects using the tailored systems engineering process, as well as the thoughts and perceptions from members in the projects are then compared to previous data obtained without the tailored systems engineering process.

The second task required a draft of the tailored systems engineering process to be developed. This was presented to the team members who were asked to comment and criticise, in order to make the process as user friendly as possible. The draft was also used by the same project members in two small scale projects to see how well the process operated. During this time, the author acted as an impartial observer, recording what was going on without influencing the participants. Feedback from this process was used to refine the tailored systems engineering process. The same team members of RobotronicsUQ then used this updated process again on a small project that was similar to the first two test projects. The results of this final application were gathered though interviews with the participants and the authors observations.

The calibration of the methods used in this case study was essential in order to produce a successful tailored systems engineering process. If the outcomes produced by the participants using the tailored process correlated with those produced by one of the authors using the full process, then the tailoring process was successful and the methods were calibrated. The aim of this study was to produce a tailored systems engineering process with the essence of system engineering still intact, but without unnecessary complexity and paperwork. It is therefore essential that the tailored process still produces the same outcomes.

4. The tailoring process

Having chosen to tailor the systems engineering process, many questions remained. What level of tailoring was required? What standard should the product produced using the tailored system be at compared to one produced using the full system? In reality, this depends upon the individual undergraduate project under consideration. In order to make a general tailored process that could be applied to all undergraduate projects the case study adopted a student's perspective to decide what level of tailoring was necessary.

Consider a student within one of these undergraduate projects who has some familiarity with systems engineering. They are given the full systems engineering process and asked to work out what parts they would need. They would naturally ask of each section "Do I need this section to develop my product, or will I be able to develop a product that will perform at the same level without it?" "Will a fellow team member be able to tell the difference in the final product if this section was included or not?"

This is the crucial point. The condition used to tailor the systems engineering process was so someone who has some knowledge of systems engineering could not tell the difference in the finished product if the tailored process was used compared to the full process. If there is no appreciable difference, then the tailoring process was successful.

Thus the tailoring process used in this study was as follows.

1. Consider each section separately, but keep in mind how it all fits together
2. Read and re-read each section to gain an understanding of what the section is aimed at doing
3. Apply the full process section by section to develop a product
4. Analyse the section with reference to the developed product to determine what can be omitted, what can be modified and what can be combined from the full process so that the condition for successful tailoring is met
5. From this analysis, develop a draft tailored systems engineering process
6. Test the tailored standard in a case study environment to produce a product using the tailored process
7. Compare and contrast this product to the initial product developed using the full process
8. Modify the draft of the tailored process so that future applications produce the same standard of final product as the full process

The tailored systems engineering process that was developed was modified extensively compared to the full IEEE 1220 process, mainly by combining some sections and removing others. All of the sections were reworded in student friendly language that was aimed at explaining what was happening and what needed to be done. In order to make it as user friendly as possible and to get the maximum benefit out of its application, a few sections were added to the original process. These were a formal inputs stage and a project overview.

The inputs stage was aimed at taking the idea for a project or product and obtaining the necessary information to evaluate what the project is about, who the interested parties are, what the project is aimed at doing and how the product will it be developed. The project overview stage was created to ease undergraduate projects into the systems engineering framework. It takes the outputs from the first phase and uses them to develop a description of both the product and the project in general. These stages then feed into the standard requirements analysis phase.

There were ninety-three sections in the full systems engineering process (IEEE 1220). In the tailored process there were sixty-two sections, all rewritten to be easier to understand and use. The tailoring reduced a 76 page standard down into a twenty page document that was customised specifically for students to use within undergraduate projects.

The feedback from the members of RobotronicsUQ was very positive. They found it a lot easier to follow and understand than the full process, and could actually see the possible benefits that systems engineering could bring. There was still a lot of paperwork in going through the sections. The team members suggested that a computer program would encourage the use of the process more than any other method.

5. Analysis of results

Based on the case study of the RobotronicsUQ team, the questions raised in the introduction can be addressed.

5.1 Is tailoring necessary?

It was clear from the initial attempt to apply a full systems engineering process to RobotronicsUQ that tailoring was necessary. Even with efforts to make it easier to use, the students involved saw it as too much work for very little benefit. It was too large and complex to be used in an undergraduate environment.

Without any systems engineering process though, the project suffered even more. The realisation that it was the lack of structure and professionalism rather than money, time or people meant that some sort of systems engineering process was required.

Thus, tailoring was necessary for the systems engineering process to be used in an undergraduate project. Would tailoring leave out too much essential information though? The answer is no. It was found that the tailored process was not only successful, but outperformed some aspects of the full process. This was largely because the focus was on the important parts of the process, and not on the non-essential paperwork and other considerations for an undergraduate project.

5.2 What is required for the project's benefit?

The sort of tailored systems engineering process that will maximise the benefit to the project is one that develops the same standard of product as the full process, but that is as easy to use as possible. This ease of use is important, as it promotes the successful application of the tailored process to the project.

RobotronicsUQ produced a product using the tailored process that was comparable to one developed using the full process. The team members that participated in the case study found it easy to use. Thus, a tailored process akin to the one developed in this study maximises the benefit to the project without overcommitting the project to useless managerial and organisational hassles.

5.3 How much tailoring should take place?

The criterion for how much tailoring should take place was one of the most important developments within the study. After careful consideration about what was trying to be achieved, the criterion was so that someone who had some knowledge of SE could not tell the difference in the final product if the tailored process was used instead of the full process. If there was no appreciable difference, then the tailoring process was successful.

How much of a difference was allowed though? Given that different people were developing the products, the final physical realisations could be completely different from each other. It was decided that as long as both of the products fulfilled the same initial requirements and had the same functional characteristics, then they could be classed as the same and the tailoring successful.

5.4 Is there ultimate benefit for the students and the project?

The application of the tailored systems engineering process to RobotronicsUQ ultimately benefited both the project and the students involved. The product developed using the tailored system was of far better quality than one developed without the process. The students felt that they had learnt much more about systems engineering from its application within the project than they would have from lectures. They also felt that the standard of the products they developed using the tailored process was what they were after.

5.5 Lessons about tailoring process

In order to use a system engineering process within the undergraduate projects that were considered in this study, tailoring was required. The hardest part about the tailoring process was working out how much to tailor, and how to try to clarify whether or not the tailoring criteria was met in each section. Once the criterion was developed, see section 6.3, again thought had to be given on how similar the products needed to be using the tailored and the full process. It had to be remembered constantly that this was for an undergraduate project. As long as both of the products met the initial requirements and had the same thoughts in their development, it did not matter if the products were physically different, as one was developed by the author using the full process and the other was developed by a group using the tailored process.

The actual tailoring process took a considerable amount of time, mainly because it was done section by section. In retrospect, if the tailoring had have been done phase by phase, i.e. requirements analysis, requirements verification etc, the process would have been faster. It also could have lead to a more succinct tailored system within each phase, as one comment was that the sections were a bit mismatched.

6. Discussion

This study set out to explore ways of introducing the discipline of a systems engineering process as a means to improve the professionalism of extracurricular, student lead design-built-perform projects. The results have implications for other student projects in engineering and for the development of the broader graduate attributes required by industry and articulated in the new accreditation requirements of engineering programs [1, 11]. It also contributes to the debate on problem-based learning methods, and in particular to the issue of how to incorporate these methods into these such engineering projects.

Students in extracurricular projects are volunteers. While they are highly motivated, equally they are likely to be even more sceptical than students in "for-credit" courses when it comes to accepting the need for a disciplined process or other management systems, such as that provided by the SE process. The students in extracurricular projects have a "can do" attitude and just want to get on with it. Most have not been exposed to the sorts of project and process management discipline that are part of professional practice and therefore do not come with an expectation or appreciation for the value of these. In contrast, students in "for-credit" courses, like capstone design projects, may be more willing to tolerate process or management frameworks required by academic staff as part of these projects, but even then they may only pay lip service to the requirements.

It is therefore significant that this case study demonstrates a degree of student acceptance and "buy-in" to having an explicit process, provided it is tailored to suit the project and it is sensitive to the students' perspectives and is not externally imposed. It suggests some conditions that should be met to gain more student ownership of the process elements in "for credit" project based learning courses.

The systems engineering approach provides a process model for undertaking design projects, linking many of the technical elements in such projects. But beyond that, systems engineering in its broader sense [12] can foster the development of many of the other broader graduate attributes demanded by industry. It embeds a team approach, including a multi-disciplinary approach. It requires a range of communication skills to be deployed including informal oral communication, formal design reviews, and project documentation. It can also provide a vehicle for incorporating issues such as sustainability, social awareness, and professional and ethical responsibilities into projects.

Problem-based learning has been established an effective educational approach to whole university programs, especially in fields like medicine. In engineering education, where projects have long been an integral part, especially in the senior years, we have tended to adopt and adapt some of the ideas from problem-based learning and use the acronym PBL meaning project-based learning. In doing so there has not always been as much emphasis on process as is the case in problem-based learning. Just having students engage in a project does not provide sufficient pedagogical framework for developing the sorts of professional competencies we would expect in our graduates. There must be some explicit process elements. But there is much anecdotal evidence to suggest that many "project-based" engineering courses focus almost exclusively on the project deliverables (the technical outcomes) and pay limited attention to providing a process framework that will foster the explicit development of other professional skills.

Systems engineering offers a means to introduce process in a form that is likely to be more acceptable to more technically oriented academics. Some of the resistance to including process elements in project courses arises from the perception that these are about developing "soft skills". This is often seen as being outside the scope of the course or beyond the expertise of the staff member. Seen as a technical process for organising projects, systems engineering offers a legitimate first step in incorporating a professional approach into such projects. But it is not limited to this narrow technical view. It opens the way to developing many of the "soft skills" associated with team work, communication, social impact, ethics and so forth. Where systems engineering was arguably a relatively narrow technical approach to handling complex projects primarily in the defence and aerospace industries, it is now understood to be a much broader rubric that can even cross into the earlier systems thinking movement.

7. Conclusions and future work

The conclusion from this study is that a tailored systems engineering process can be developed that benefits both the students and the project. This can be used as part of the education of students about systems engineering, as well as helping them develop their graduate attributes.

The direct future work from this study is the development of a set of tools to aid in the use of the tailored systems engineering process. The tools would have to be easy for the students to access and to use, and help guide the students through the tailored process step by step. It should also be able to be modified in accordance with the type of undergraduate project using it. If the project is a very basic one, a more tailored version of the process should be able to be used.

The most effective implementation would seem to be a web based tool, able to be accessed by anyone in the team conceivably anywhere in the world. Included with this could be a virtual office to store online documents and specifications as well as to conduct meetings and plan the project. Future work in this area would look at existing web-based computer applications and conducting a critical review of them, based on the results from this study. This could then be used to develop a web-based tool that incorporated the critical review and the tailored systems engineering process.

Another area of future work would be the integration of a tailored systems engineering process into a project based courses as part of the curriculum. This would run in conjunction with traditional lectures, with the material from those lectures feeding in to the project.

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