Complex Engineering Design: Project Based Learning Incorporating Sustainability and Other Constraints

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BACKGROUND
Traditionally, engineering education has focussed primarily on developing the technical skills of engineering students. However, as a result of the evolving requirements of engineering accreditation stipulated by the Washington Accord, there is an increasing need to better integrate the contextual aspects of engineering practice within the curriculum (Hodgson & Williams, 2007). To address this, Massey University has recently redesigned its engineering programmes, and has introduced a project based 'Engineering Practice' spine that runs through all years of the programme. One of the main purposes of the project spine is to develop a holistic view of engineering, and provide both a focal point and motivation for the technical papers. In the early semesters, the focus of the project is on developing the core concepts and building the mindset of integrating contextual aspects. This paper focuses on the third year project, which builds on and integrates these through a year-long technical project that addresses design with constraints, incorporating societal, environmental, and financial constraints.

PURPOSE
The purpose of the third year project is to expose the students to a complex engineering design project, with an emphasis on working with constraints. In developing their solutions, students have to consider the triple bottom line (incorporating financial, social, and environmental constraints). A holistic approach to sustainable development is critical and that inter-relationships and interdependencies must be recognised between people, the environment and the economy as core requirements of sustainable development (O'Sullivan & Painter, 2007).

DESIGN/METHOD
Project-based learning (PBL) is employed as a comprehensive tool to engage students in investigation of complex problems (Blumenfeld et al. 2011). The class consists of a mix of mechatronics, electronics and product development students, formed into multi-disciplinary teams of four students each. The project is split into four phases, beginning with defining the project and product context, through to developing detailed design specifications, implementing a working prototype of their design, and finally, developing a commercialisation plan, with sustainability as a core marketing platform.

RESULTS
From a student learning perspective, we expect the students to be better equipped at applying social and environmental constraints and interactions to technological design. Already we have seen effective project planning from the students, through the setting of their own milestones, and effective teamwork, through the division of tasks to different team members. From student reflections, many of the students appreciate the need for a holistic approach to engineering design, rather than purely a focus on the technical aspects.

CONCLUSIONS
The complex design project is ambitious, in that it stretches the students, and extends the scope of real engineering design. The students have risen to the challenge, and we have strong and enthusiastic engagement from the whole cohort. From student reflections, they are integrating practical engineering skills with their technical knowledge.

KEYWORDS
Project based learning, self-management, sustainability

Introduction

Traditionally, engineering education has focussed primarily on developing the technical skills of engineering students. However, as a result of the evolving requirements of engineering accreditation stipulated by the Washington Accord, there is an increasing need to better integrate the contextual aspects of engineering practice within the curriculum (Hodgson & Williams, 2007).

The International Engineering Alliance's (IEA) Graduate Attributes and Professional Competencies (IEA, 2009) adopted by the Washington, Sydney and Dublin Accords required signatories to review their current standards. Within New Zealand, this prompted the Institution of Professional Engineers New Zealand (IPENZ) to formulate the National Engineering Education Plan (IPENZ, 2011) defining the gap between IEA's graduate exemplar and the current IPENZ accreditation criteria and graduate profile. The key outcomes were:

- There is a need for professional engineering graduates who are "rounded" and not just technical boffins – many of the existing graduates do not have strong "soft" skills.
- Professional engineering graduates should aspire to leadership roles, and their education should equip them to commence their preparation towards such roles.
- Graduates entering industry have technical knowledge that is largely theoretical, and industry needs to invest considerably to close off the knowledge gap between principles as taught and codified knowledge as used in industry.
- Graduates entering industrial research roles require research skills.

To address the identified gaps and to integrate the contextual aspects of engineering practice, Massey University has recently redesigned its engineering programmes, and has introduced a project based 'Engineering Practice spine' that runs through all years of the programme. One of the main purposes of the project spine is to develop a holistic view of engineering, and provide both a focal point and motivation for the technical papers.

In the early semesters, the focus of the project is on developing the core concepts and building the mindset of integrating contextual aspects. In later years the projects build on and integrate the core concepts through year-long technical projects that address design with constraints, incorporating societal, environmental, and financial constraints. This paper focuses on the year-long project in Year 3.

Project based learning

Project-based learning (PBL) has often been employed as a comprehensive tool to engage students in the investigation of complex problems (Blumenfeld et al., 2011). PBL is a comprehensive approach to classroom teaching and learning that is designed to engage students in the investigation of real-world problems that involve students in design, problem-solving, decision making, or investigative activities. The projects culminate in realistic products or presentations (Jones, Rasmussen, & Moffitt, 1997). Projects have the potential to motivate students and provoke thoughts for deeper learning. The project based learning approach is however not devoid of difficulties that both students and teachers encounter; extra efforts are required to sustain motivation and thought.

In most PBL exercises that are documented in the literature, the emphasis has been on the technical solution and learning alone. The contextual aspects, constraints and the collaborative approach to interdisciplinary learning are equally important but are often neglected (Jones, Rasmussen, & Moffitt, 1997). A holistic approach to sustainable development is critical and that inter-relationships and interdependencies must be recognised between people, the environment and the economy as core requirements of sustainable development (O'Sullivan & Painter, 2007). Many current university programmes lack emphasis on developing professional practice attributes and the wider contextual aspects of engineering practice. The research ability (to delve deep towards the frontiers of knowledge) of graduates is sporadic. There is also the lack of a universally accepted model or theory of Project-Based Learning (Thomas, 2000).

CDIO (Conceive-Design-Implement-Operate) principles, used in designing curricula, also emphasise the importance of integrated learning experiences that lead to acquisition of disciplinary knowledge, as well as personal, interpersonal, and product and system building skills (Bankela et al., 2003). Another CDIO principle stipulates teaching and learning based on active experiential learning methods (CDIO, 2004). In support of these principles, the project spine provides continual reinforcement of active and experiential learning.

The Duck Project

The precursor to the 3rd year project paper of the new redesigned BE structure is the 'Duck project' which was part of the 2nd year introductory electronics papers (Bailey *et al*. 2000; O'Driscoll *et al*. 2001, Bailey *et al*. 2004). Students worked together on a group project in parallel with their regularly scheduled lectures and laboratories. Each team of four students had to design and construct a complex electronic system. The staff involved with the project acted as consultants to the design teams. The project was integrative in that it combined together a wide range of tools and techniques from across the spectrum of topics covered in lectures. For each module, students were required to design a suitable circuit to meet explicit specifications, verify their design through simulation, prototype their design on breadboard, and realize their design on a PCB. By running the design project in parallel with the theory, the project improved the students understanding of the theory at the same time as developing design skills.

The duck project provided the scope for excellent experiential learning of technical things, team work and to some extent communication skills, but lacked the contextual nature of the design and development exercise. It did not address important issues such as sustainability, societal and cultural impact of engineering design, safety and health, corporate and professional ethics, and project management. Moreover the technical specifications of the project were predefined and the knowledge discovery was confined to only those areas that were required to meet the specifications.

Approach

The core and facilitating concepts that are fundamental to the capability of technologists and engineers are shown in Figure 1. The understanding and application of each of these concepts is the common theme that runs through the project spine. The goals of the project papers are to embed the core concepts of problem goal definition, definitive action, decision making and systems thinking. The project papers also develop the additional skills and knowledge required for a well-rounded and highly capable engineer such as teamwork, communication, context analysis, knowledge discovery, personal skills and attitude, project planning and management, and professional skills and attitude.

Overview of project papers

One of the emphases of the early papers is the need to gather relevant data to make decisions, with the quality of the resulting decisions dependent on the quality of the data gathered. Students have to complete a project (per semester or double semester) that involves utilising the common practice of the engineering method to solve a variety of open-ended problems. The scale, complexity and realism of the problems, and the sophistication and technical contents of the students' solutions, increase as the students advance through the four year programme. This culminates in a capstone project, sponsored by an industry partner, in the final year that engages student teams in significant design problems with realistic constraints. A brief description of the project papers follows.

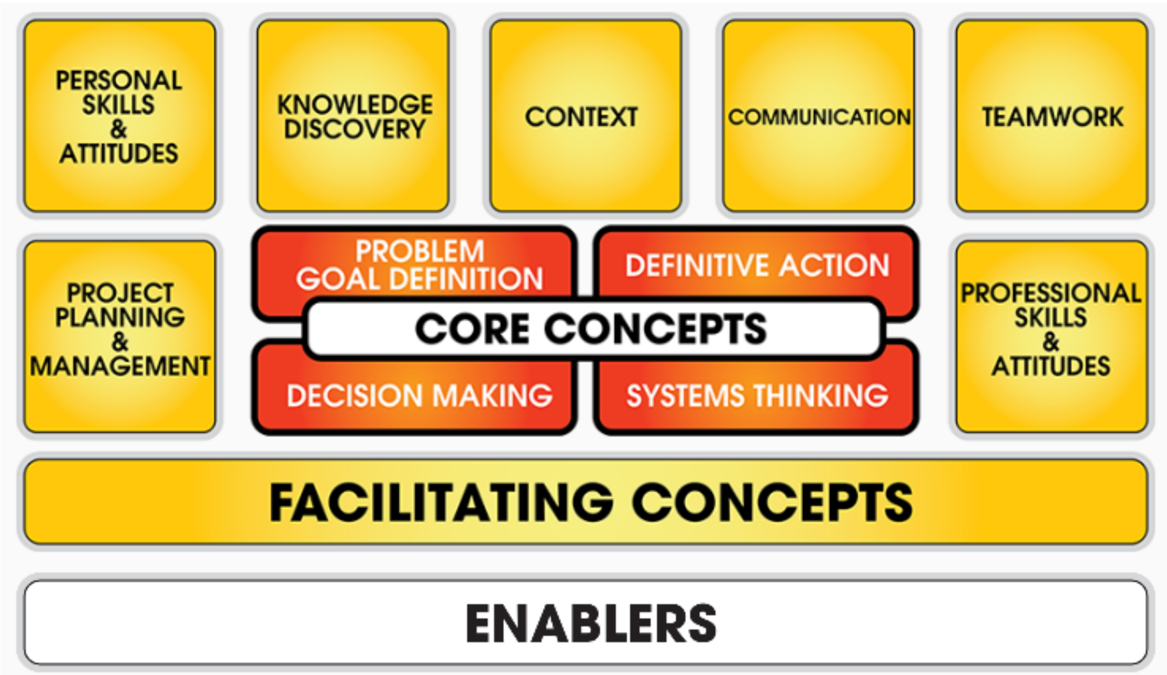

Figure 1: Core and Facilitating Concepts for a professional engineer

The semester 1 project paper brings a global perspective through the Engineers without Borders (EWB) challenge (an Australasian design program for first-year university students). This project has well-defined system boundaries, stakeholders and deliverables, where significant support is provided with information and decision-making. Students work in teams to develop conceptual designs for projects that contribute towards the sustainable development of disadvantaged communities. Students develop a solution to a specific problem in a developing country. Application of appropriate contextual knowledge to a solution which is fit for purpose (socially, financially and technically) is central to project success.

The semester 2 project paper develops creative solutions through design for a scenario 50 years in the future. This project requires the definition of system boundaries and deliverables where information is both ambiguous and incomplete. Clarification of project definition and dealing with uncertainty is key to project success. The students develop a scenario for the year 2070 based on specific dimensions of society, environment, government, trade, technology etc.

The semester 3 project paper looks at product development. This project is based on the context of a specific company or industry requiring the definition of system boundaries, the identification of constraints and decision making based on uncertainty (mainly related to market information) and trade-offs (mainly related to prioritization of product features).

The semester 4 project paper focuses on manufacturing aspects. The project involves planning the launch (i.e. designing and testing the machine and meeting the initial marketing plan) of a new coil winding machine, which is complementary to a company's existing range. The Company is of medium size and is well established as a supplier of a range of coil winders, mainly to Europe.

The Year 3 (semesters 5 and 6) project has a strong technical focus and the students design a product with constraints with special emphasis on sustainability. The project is based on the design of an educational robotic game. The context for the project is well defined, centred on a hypothetical New Zealand based company that has experience in the design, manufacturing and marketing of robotic toys and is seeking to expand into the European market with an educational toy based around robot soccer. Although there is significant freedom in the development of the design concept, significant constraints are imposed in terms of the target market, basic elements of the game, educational requirements, and development budget. Sustainability is imposed as an essential requirement for the final product concept, particularly emphasising WEEE & RoHS legislation and LCA analysis.

Although a clear design brief is provided, the level of direction and supervision is significantly reduced, relative to previous projects. Definition of team goals and milestones, allocation of individual responsibilities (based on disciplines) with the team, and overall project management are central to successful project outcomes and assessment. A strong emphasis is also placed on technical problem solving, using knowledge from within the programme and acquiring knowledge required to resolve specific project issues.

The Year 4 (semesters 7 and 8) capstone project focuses on bringing together all their technical skills, and applying to a complex engineering problem. This project is regarded as the culmination of the degree – the bringing together of all learning from throughout the programme and a demonstration of the students' ability to clearly define the scope, outcomes, and deliverables from a complex engineering problem, and to enable successful resolution of this problem through appropriate project planning and implementation. As such, the project places significant demands on the student to solve a problem of significant complexity, where complexity is largely defined by the breadth of scope and the need to seek and resolve inputs from a broad range of stakeholders and disciplines. A particular feature of the capstone project is the requirement for the students to take full responsibility for project definition, planning and completion with limited supervision and guidance.

In the 4th year, students also undertake an individual research project.

The results of this project based spine approach is that students gain experience at developing technically detailed problem-solutions, and develop other attributes, such as communication, teamwork, financial and sustainable design skills.

Requirements for the 3rd year project

To address the Washington Accord attributes for a range of engineering activities and problem solving, the following requirements were set for the 3rd year project:

- The design exercise must address sustainability issues with emphasis on consequences to society and the environment
- In-depth market research and legislative requirements, including health and safety, must precede and inform the activities in the technical design phase.
- The project must be integrative providing scope to combine together a wide range of tools and techniques
- The project must not have an obvious solution and require abstract thinking, innovation and exploration of diverse methods to solve a problem. It must provide the platform for the students to learn how to learn.
- The project must be undertaken in a multi-disciplinary group to develop skills in team management, project management and communication
- The project complexity should be such that it involves wide-ranging, even conflicting, technical, engineering and other issues.
- Students learn to self-manage resources, such as time and money, by proper planning and setting their own milestones.

How we have achieved it

Students have been given the context of working in a product development team for a company called Products with Purpose (PWP). This is a privately owned, small-medium enterprise, with a fundamental ethos related to ethics and sustainability "Profit is important but not at the expense of people and planet". Students are tasked with developing an educational toy based around a robot soccer game. The product was targeted at 13 to 17 year olds, with a special focus on the Western European market.

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The class consists of a mix of mechatronics, electronics and product development students, formed into multi-disciplinary teams of four students each. Robot soccer was chosen because a successful robot soccer implementation must tightly integrate knowledge from a wide range of disciplines: mechanical design for the chassis, drive mechanism and kicking mechanism if incorporated; electrical design for motor driving and power systems; microcontroller and embedded systems for motor control; communications; image processing; and high-level programming for multi-agent control and coordination. Such a broad scope works well with multi-disciplinary team based design, because there are sufficient tasks to distribute them among the different team members. Indeed, the scope is sufficiently broad that it requires the students to divide the tasks among themselves to complete the project within the time available.

In our initial thinking, the goal was for each team to develop a 3 player team of robots, following the FIRA Mirosot restrictions (FIRA 2008). However, with further consideration and discussion, we realised that this significantly constrained the student designs and provided limited scope for contextual analysis. By removing the FIRA restrictions, and allowing any robot soccer inspired educational toy allowed greater scope for the student's creativity, and enabled a more realistic analysis to be performed.

To force the students to consider sustainability issues within their design, the target was specifically aimed at the European Union because of their more developed regulatory requirements, particularly in terms of use of hazardous substances (EU, 2011) disposal of electronic waste (EU, 2012) and packaging.

As a further constraint, each team had a strict development budget of $1000 to cover materials and components used for prototyping their design. Students were responsible for the purchase of their components, with all orders passing through a staff member acting as purchasing officer. The purchasing officer maintained an account of each team's spending, and ensured that the spending conformed to the University's financial policies.

As outputs, each team had to produce a fully developed and working prototype of a soccer robot kit ready for commercial scale-up. This included kit assembly instructions, full documentation, sample code, packaging, and the educational features including lesson plans where appropriate. Students also needed to provide a detailed commercialisation plan centred on their target market, and a production plan.

Course Structure

The project represents 25% of the student's work during their third year. Its scope requires the project to run over two semesters. One day per week is dedicated to the project – students have no other classes on that day. This enables them to spend concentrated time focusing purely on the project.

At appropriate stages within the project, primarily during the first semester, students are given weekly briefings by expert staff and guest lecturers. The purpose of these briefings is to review aspects of the students' knowledge relevant to the project, or to outline key areas of new knowledge which students would need to research for themselves. This included topics such as: sustainability, ethics, social responsibility, triple bottom line, regulatory framework, market research, technologies (motors, batteries, communications), motor control, image processing, multi-agent control. Sometimes the briefing would take the form of a workshop, where the students learn by doing. Workshops were held on sustainability (performing a preliminary life cycle analysis), functional analysis (setting appropriate technical specifications), and use of Altium designer for printed circuit board design.

To guide the students in their planning, and provide structure for setting appropriate assessments, the project was split into four phases. The first defines the project and product context, relating to market research, regulatory requirements, and sustainability. The second phase develops detailed product design specifications, including preliminary prototyping to resolve technical uncertainties, and includes a comprehensive analysis of ethical and sustainability impacts of their design. Phase three involves design for manufacture, including implementing a working prototype of their design. The final phase is developing a commercialisation plan, including production and marketing planning, with sustainability as a core marketing platform. Each of these four phases and associated assessments will be described in the next section.

Student Assessments

The milestone for the first phase was a technical report describing the project context. This consisted of two main sections: outlining the commercial and technical factors. The commercial analysis included market research and an analysis of competing products, leading to an initial product concept and target price point. This should lead to a preliminary pre-design concept of their product. The technical analysis required students to research available technologies relevant to their project. The purpose of this was not for selecting particular technologies at this stage, but to gather available information, and perform a comparative analysis of the strengths and weaknesses of different alternative approaches. The goal is not to select particular components for their design, rather to build an understanding of what is available.

In parallel with their contextual analysis, students were learning about sustainable design principles. These were assessed by an individual on-line test.

The second phase required the students to develop detailed design specifications for their product. This was assessed by a specification report, where students analysed the functional description of their design, and evolved this into technical specifications for their product. The design was then decomposed into a set of interconnected modules, with the top-level specifications translated down to module level specifications suitable for the selection of components. Each specification required adequate justification, whether from technical, regulatory, market, or sustainability considerations. Within the report a detailed analysis of the sustainability impact of their design was required.

In setting the technical specifications for their design, there are often many unknowns. Students are expected to perform any preliminary prototyping necessary to resolve any uncertainties within their design. Any such prototyping is expected to be fully documented, effectively using short laboratory reports, starting with the unknown or uncertainty, the method used to resolve the uncertainty, the measured results, discussion, and finishing with the conclusion, or resolution of the uncertainty. This emphasises the use of prototyping as a tool for gathering appropriate data for decision support. Preliminary prototyping is assessed through interview with each team, including inspection of corresponding documentation. The interview also served to provide feedback on their design specification report.

At the end of the first semester, each student was asked to reflect on their individual and team performance so far within the project. One of the goals of the reflection is to get the students to take responsibility for their own development as professionals. Having a mid-project reflection enables students to change the way that they, or their team, operates to maximise the benefit gained from the project.

Teams also prepared a detailed plan for the remainder of the project, with milestones at the end of weeks 3, 5, 7, and 9. For each milestone, each team had to document what would be completed, including detailed assessment criteria or metrics for measuring their success at each of these milestones. After grading, and feedback, teams were given the opportunity to revise their plans and assessment criteria.

In the second semester, students focussed on the third phase of the project: detailed design for manufacture, and developing a prototype capable of demonstrating the form and functionality of their product. For each of the milestones in the project plan, the teams were required to evaluate their progress using their milestone assessment criteria. Getting the students to evaluate themselves reinforces the requirement to set appropriate milestones and assessment criteria. The results of the self-evaluations were moderated through a 15 minute interview with each team. This ensured that the teams were not being overly easy or hard on themselves. The third phase culminated in a report detailing their design, including their full range of augmented product features, and providing a manufacturing production plan.

The final phase involved commercialisation planning. This was assessed through a commercialisation report. This had two components: test marketing, and marketing plan. Test marketing required demonstrating and testing their prototype against their product design specifications in a competitive situation. The marketing plan describes the teams price, promotion, and distribution strategy, with a specific emphasis on the target market defined in their context analysis. A focus on sustainability and learning through play are core marketing platforms.

Each team also had to make a presentation to the company directors, providing all of the information required for them to determine whether or not to proceed with the product. Each student had to be responsible for part of the presentation, allowing each student to be assessed on their presentation skills.

Finally, each student submitted an end of project reflection on what skills they had learned, and what skills they needed to develop further. The primary purpose of this reflection was to foster an attitude of life-long learning, and ongoing development.

Provisional Results

A qualitative evaluation of the project indicates that it is ambitious and technically very challenging. It is perhaps a little too big with many complex technical factors to be integrated. However students have risen to the challenge and some excellent products have been conceived, designed and implemented.

Feedback was gathered from the students through formal staff-student liaison meeting and informal discussions. The following is a summary of the discussions-

- There is too much context which has delayed the students in getting to the technical design
- Some groups have struggled to set an appropriate scope for the project which stems from the lack of prior experience
- Many students have struggled to practically integrate the sustainability aspects within their design
- Most students agree that the project has given them scope to acquire greater technical knowledge and appreciate the wider context of engineering problem solving.

The self-reflection reports from the students indicate that many still find it difficult to self-manage time. Some students have grossly under-estimated the time it takes to order components and get them in. This has hindered their progress in prototyping and testing the design.

Discussions and Conclusions

The CDIO standards have been used to benchmark the redesigned BE program. The new curriculum has been designed in a systematic and holistic manner addressing the requirements of the Washington Accord. Table I shows the Washington Accord attributes for a range of engineering activities and how these have been addressed in the 3rd year paper. Table II shows the attributes for problem solving and how these are addressed in the paper.

2014 was the first year of implementation of this project paper. Significant challenges were encountered by staff as well as students. In the beginning of the project it was difficult to make the students see the holistic picture i.e. designing a product with constraints. Students wanted to get stuck into the technical design and development of the product without analyzing the market or surveying the technologies. An additional workshop had to be organized to drive home the importance of incorporating sustainability principles in the design.

Students have gained greater technical knowledge in the area of engineering specialization. From the work done it is evident that students have called on all existing knowledge, as well as specifically identified new knowledge, to identify, evaluate and define specific design solutions, within the contextual constraints. The level of direction and supervision is significantly reduced from previous projects requiring greater self-direction by the students. Overall the project is ambitious and technically challenging but eventually the students have risen to the challenge. The project paper fully meets the Washington Accord requirements.

Table I: Washington Accord attributes for a range of engineering activities

Attributes	How the attributes are addressed
Range of resources Involve the use of diverse resources (and for this purpose resources includes people, money, equipment, materials, information and technologies)	A team project, with each member allocated an individual responsibility or portfolio e.g. mechanical, electronics, commercial. A $1000 budget is allocated to each team and must be accounted for. No specific labs or workshops are scheduled. Teams must manage and schedule their own resource requirements.
Level of interactions Require resolution of significant problems arising from interactions between wide-ranging or conflicting technical, engineering or other issues	Effectively a product development project requiring the integration of a range of inputs and resolving different stakeholder requirements in the design process. Of specific importance is the application of sustainability principles and resolving trade-offs between sustainability and other market/commercial and health and safety drivers.
Innovation Involve creative use of engineering principles and research-based knowledge in novel ways	Novelty in product design and use is an essential consideration. Identifying novel and attractive product features which meet the gaming as well as the educational needs. Research-based knowledge is generated, evaluated and applied to derive technical and commercial solutions that meet the prescribed needs.
Consequences to society and the environment Have significant consequences in a range of contexts, characterized by difficulty of prediction and mitigation	A key focus is trade-offs related to sustainability drivers relative to commercial and technical requirements.
Familiarity Can extend beyond previous experiences by applying principles-based approaches	This project presents significant challenges beyond what students have experienced in previous projects – in particular project management and the strong emphasis on meeting challenging technical problems through application of sound problem solving principles informed by existing and new knowledge.

Table II: Washington Accord attributes for problem solving

Attributes	How the attributes are addressed
Depth of Knowledge Required Cannot be resolved without in-depth engineering knowledge which allows a fundamentals-based, first principles analytical approach	Although based on a product development challenge, this project requires significant emphasis on the application of engineering fundamentals in mechanics, electronics and computing. Existing knowledge and new knowledge from research literature is required. Demonstration of sound engineering design principles and problem solving is essential.
Range of conflicting requirements Involve wide-ranging or conflicting technical, engineering and other issues	This project, titled “design within constraints” is intended to challenge students to address a wide range of conflicting issues – primarily around commercial and sustainability drivers, addressing a range of technical solutions and evaluating these technical options against project constraints. The challenge with this project is not simply to develop a working prototype of a robotic game but also to design the augmented features of the product that promote its educational value.
Depth of analysis required Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models	There is no prescribed solution to this project. Creative thinking in terms of the product concept, its technical and augmented features, and the application of appropriate technologies to deliver this concept, is central to the project.
Familiarity of issues Involve infrequently encountered issues	The technical and contextual challenges of this project are likely to be unfamiliar to most students.
Extent of applicable codes Are outside problems encompassed by standards and codes of practice for professional engineering	Product development is a multi-disciplinary activity requiring recognition and application of a range of standards and codes from disciplines other than engineering – legal, marketing, finance etc. As the project is directed at the European market students have to comply with legislation such as WEEE, and RoHS directives.
Extent of stakeholder involvement and conflicting requirements Involve diverse groups of stakeholders with widely varying needs	WP6: Stakeholder identification, definition and resolution of conflicting needs are an important basis for the project. Stakeholders include young people (14-17 yr. olds), manufactures, and distributors.
Interdependence Are high level problems including many component parts or sub-problems	WP7: Their chosen product may include a number of subsystems (ranging from 6-10) and components. Students must address the design of each component separately and in combination with the other components.

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