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TOWARDS A NEW STANDARD FOR FEA METHODOLOGY AND PRESENTATION IN PRODUCT DESIGN PORTFOLIOS

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ABSTRACT
This paper presents the outputs from a taxonomy of senior year Product Design student projects uncovering common trends in the application of computer-based simulation, primarily Finite Element Analysis (FEA) in the delivery of creative product solutions. The 2 cohorts within the analysis develop their own product design briefs and are challenged to integrate their previous knowledge with new project-based learning. Where FEA is a relatively small component of the design curriculum, but one of the most likely forms of analysis within product design engineering work, the successes, mistakes, missed opportunities and shear variety of analysis opportunities can inform developments within FEA pedagogy in design centred engineering. Often students must make considerable leaps to move from familiar textbook problems to their own project work, and it can be difficult for multidisciplinary teaching staff to support the integration of FEA into project work. The paper presents our evolved curriculum thread, and aspects of pedagogy, aiming to link analytical classes with project modules in the middle years, and support senior project students applying FEA techniques to their own design concepts. The paper concludes by summarising future priorities towards consistent excellence and attainment for product design centred FEA methodology and its presentation within the design portfolio.

Keywords: FEA, finite element, design analysis, product design folio

1 INTRODUCTION
The work outlined in this paper was initiated through reflections on 15 years' experience of teaching engineering design (design analysis and machine element design) to Product Design Engineering students at the centre of their undergraduate degree; the Engineering Design module in year 3 (see Figure 1). When first involved in teaching this subject, all design analysis was based on hand calculations and paper based graphical methods; it has evolved to integrate computer-based analysis. The module is the most substantial teaching and assessment of FEA in the curriculum. Upstream assessment criteria for final projects are not explicit on analysis type, but the majority of students include FEA. This work is a reflection on qualitative attainment within our curriculum and final project deliverables, and on experience of integrating FEA as a personal skillset and teaching specialism. The overarching aim is to explore integration of curriculum learning in FEA into design project methodology, how it develops in project based learning and to identify priorities for future intervention.
Computer analysis in product design discipline will be discussed before presenting our curriculum. Cohorts of Product Design Engineering student folios are analysed to create an outline taxonomy of FEA in project work. It is hoped that the analysis will be of interest to students, supervisors and assessors considering FEA and other curriculum design tools/methods pivotal to project success. Similarly, curriculum designers/maintainers may be interested in the fuller curriculum.

2 FEA IN DESIGN EDUCATION
Whilst Finite Element Method and the Analysis technique based upon it, FEA, have been increasingly used in industry and academia since the 1950s, it has been computer developments in recent decades that have seen tools move from mechanical expert domains, to being integrated and increasingly useable CAD tools for the competent technical product designer.

There is a challenge in design education around the ambiguity in the gap between the traditional FEA specialist and the multidisciplinary product designer [1]. There are texts aiming to define the designer

as a pragmatic FEA user [2-4] but it can still be difficult for both educators and students to pinpoint the correct level of "rigor" in product design FEA studies. None the less, the creative design engineer demonstrably capable in CAD based analysis is a highly desirable and valued profile in industry.
Engineering educators at Wentworth Institute of Technology [5] and others of the ASEE [6] have regularly written of teaching philosophies and case studies around strategic use of FEA in mechanical design. In this conference series we have considered the integration of engineering fundamentals in design projects [7], innovation in machine elements [8], and specific simulation types such as topology [9]. There has been relatively little explicit discussion of the teaching, learning and overall impact of computer-based analysis within Product Design projects. An explicit account is attempted here.

3 CURRENT APPROACH

Figure 1 shows 3 key themes of the Product Design Engineering curriculum instrumental to integrating mechanical design analysis with product design project methodology. Module size indicates relative contribution in terms of credit weighting. EE, fluids, maths, mechatronics, Industrial Design, production techniques and management are other compulsory themes not shown here.
Locally, the author has a relatively unique vantage point to evaluate engineering design and FEA teaching and learning through holding organising roles in Integrating Project 2 and Engineering Design, as well as tutoring analytical aspects of Design 2 and Integrating Project 3. All teaching staff supervise and assess individual projects and can observe how their curricular contributions may manifest within.

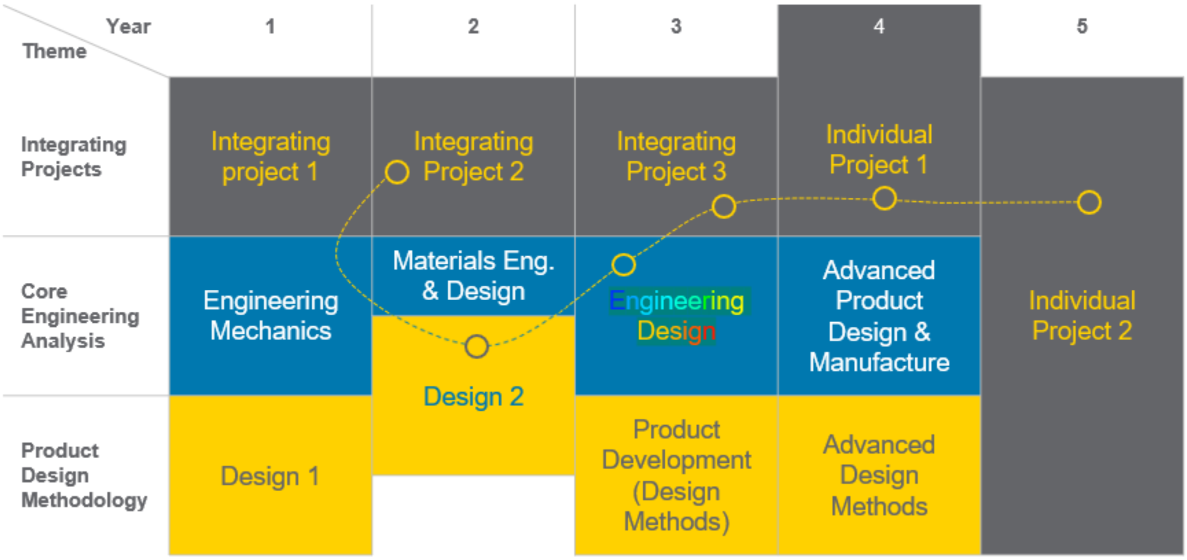

Figure 1. Partial PDE Curriculum showing relative module contributions directly relevant to FEA evidenced in Individual Projects 1 and 2. The author's involvement superimposed on the figure

3.1 Integrating projects and design methodology

Integrating projects 1 and 2 focus on CAD/CAM (including professional certification) and practical product build skills. Design 2 continues design methodology themes from Design 1 but with 25% of the module focused on integrating the engineer's bending formula and graphical force analysis techniques to analyse a product conceptualised by students. It is building upon year 1 Engineering Mechanics and introducing a pragmatic "designer" approach to analysis in a real product context. The project aims for a sense of iteration in analysis and Factors of Safety (FoS) to select section sizes and materials.

3.2 Engineering Design class and integrating project 3

Engineering Design in year 3 begins by revising product failure through bending, but quickly expands to reveal further failure modes – deflection, von mises stress, fatigue, buckling, stress concentration, motion loads and contextualized in machine element design for product design. Computer analysis techniques are introduced immediately for beam bending and sustained throughout the syllabus. To create a bending moment diagram in the CAD package requires students to learn the same steps for 3D FEA analysis – apply fixtures, apply loads, mesh and solve. Using a single software tool to bridge between simple 2D beam solutions and analysis of 3D multi plane stress parts leads to very smooth transition into the FEA topics and assessment. Students are tested every 3 weeks and are encouraged to use the software in the tests to check answers for simple and multi-plane bending/torque problems. The final test is a specific FEA assessment which advances the basic approach into analysis requiring advanced mesh control, split lines and more detailed fixture application to more complex geometry solid models. In parallel, the students are undertaking an embodiment product design project in "Integrating Project 3"; the author is involved in both modules highlighting linkages between the syllabi, introducing further CAD analysis such as topology study, virtual drop testing and strategies for converting 3D 'design models' to 'FEA models'.

3.3 Year 4

Advanced Product Design and Manufacture and advanced Design Methods in year 4 go into depth on other computer design support tools; DFMA and material selection, but do not currently expand on FEA. Some students may cover further FEA topics through optional module choices, and all are required to demonstrate "engineering analysis" in their "individual project 1" (worth 33% of year 4) and Individual Project 2 (worth 50% of their final year). In the projects students develop their own product briefs and are challenged to integrate previous knowledge with new project-based learning; it is difficult to balance new, exciting briefs with specific engineering opportunities. The majority do choose to utilise FEA.

4 FEA IN THE DESIGN PROJECT FOLIO

FEA is increasingly assumed essential to evidence analysis in projects. This is not necessarily problematic, but purpose in analysis is not always well articulated. Raw screenshots of an FEA analysis of the students' own design work can create an immediate impression of "rigor" in embodiment design, but that should only be concluded when more subtle quality indicators in FEA process are evidenced.
These projects cover so much ground – technical/market/user research, electrical/mechanical, prototyping, project management, systematic creativity, commercial aspects etc. Although not central, when scrutinised, FEA can also reveal significant insights into students' understanding. A light touch in analytical work more generally; a lack of iteration and optimisation of the design. Where simulation results are presented without discussion of setup and reflection on the implication of results on the design (see figure 5a.), the inclusion of FEA can undermine the project rather than bolster it. The decision of "great, some analysis is included" ☑ or "there is a lack of understanding of key principles of analysis" will come down to the other analytical strengths of the project.

5 STUDY APPROACH

Table 1 sets out parameters of the study. 'Individual Project 2' folios of 2 cohorts of students were analysed. Both cohorts have followed the curriculum path shown in Figure 1. Cohort 1 was chosen as an additional optional FEA "good practice" workshop was provided during embodiment design phases. The workshop included a tutorial/demonstration [4] and review of project folio examples and was attended by 10 students. Cohort 2 did not have this workshop opportunity.

Table 1. Study Sample Parameters

Cohort	Course	Samples	FEA Workshop	Lab access
1	Final Year MEng PDE	29	Optional (10)	Full
2	Final Year MEng PDE	29	No	Limited

Cohort 2 undertook their project without full access to prototyping facilities (COVID Pandemic restrictions) and therefore, interestingly, may have had higher reliance on virtual/simulation platforms. The author performed all analysis of the folios. An initial coding scheme was expanded/refined during the reviews. Table 2 provides an overview of criteria. All submission documents were reviewed where FEA results and discussion may by spread over report and folio documents.

Table 2. Study Criteria

Criteria	Explanations/Expectations	Quality Indicators
FEA relevance	Was it relevant and implemented?	Clear choice to include or not.
Study Types	See table 3 for range.	Discerning selection
Study Setup	Model simplification, fixtures, loads, mesh control, part vs assembly.	Highlighting decision making even when defaults are accepted.

Results and reflection	Reaction forces, stress, strain, displacement, Factor of Safety, clarity of presentation.	Clear results extracted and some interpretation of results against design goals.
Validation	Cross referencing hand calcs or other data, check reactions.	Inclusion of some datum to validate that the numbers are realistic.
Impact	Was there clear intention?	Design revisions, clear decisions.

6 RESULTS

6.1 FEA relevance to project

24% (7) of cohort 1 did not complete FEA. These projects had either a bigger focus on electronic functionality (monitoring sport and sedentary behaviour) or struggled with complexity of surface models (2 x helmet designs) or water systems (irrigation kit). 2 students acknowledged that they would have ideally included CAD analysis. In cohort 2 17% (5) did not include FEA. In one case a highly detailed paper based analysis of tyre pressure control system was included. A student documented that FEA had failed in the time available, the 3 remaining did not provide alternative analysis.

6.2 FEA Study Types

Table 3. Distribution of FEA Study Types % (no. of Students)

	Static	Drop Test	Topology Study	Fluid Flow	Thermal	Fatigue	Mold flow analysis	Beam bending	Non-Linear
1	100 (22)	18 (4)	18 (4)	9 (2)	3 (1)	7 (2)	7 (2)	0	3 (1)
2	91 (24)	38 (9)	4 (1)	8 (2)	8 (2)	0	8 (2)	4 (1)	0

A potentially interesting difference is that some students in cohort 2 did only dynamic testing. It can be difficult to define use situations for some encased products, and the "drop test" offers eased dynamic impact testing. There were less topology studies in cohort 2, but topology was no less relevant to project models. Another student in cohort 2 generated bending moment diagrams in CAD finishing stress calculations by hand. As can be seen from the table many students undertook multiple study types, although none could be considered to have utilised multiphysics approaches.

6.3 Study setup

There was scope for better communication of the aim of studies and the explanation of the study setups. Figure 2 shows an example where the student provided a clear explanation of how the orthotic would be modelled and results utilised. Accompanying discussion provided rationale for these parameters, but many assume the reader can interpret from raw results alone (see Figure 3b). Figure 3 (a) shows an example of where the student was explicit in how the model fixtures and loads were applied, although not discussing how those were determined. Figure 3 (b) shows that a force has been applied to the whole face of a part when the use case of the product did not seem to warrant this.

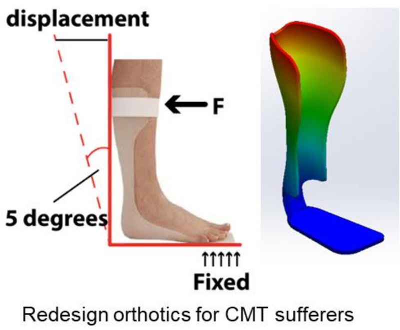

Figure 2. Clear setup example

In contrast, Figure 3 (c) shows a model prepared so that the force was strategically applied to match the use scenario. Only one project in cohort 1 and two projects in cohort 2 explicitly discussed mesh control. In one case mesh density had been increased to improve accuracy. In another (Figure 4a) this had been strategically done, in the way that had been promoted and assessed in year 3 class tutorials. In the majority of projects, the analysis is applied to a single part extracted from an assembly and therefore it is important to explain how the fixtures and forces reflect the assembly relationships. 38% and 36% of the cohorts analysed full assemblies, but only one student actually discussed how they had dealt with component interactions and contacts (Figure 4b.).

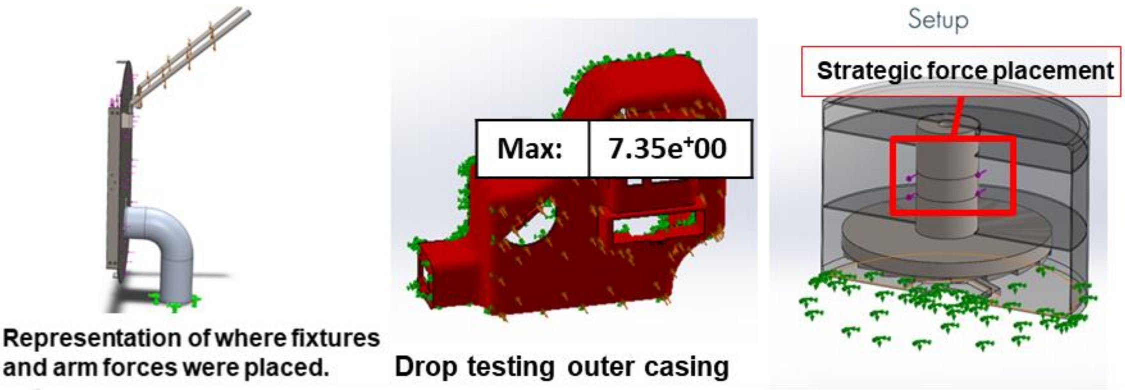

Figure 3. (a) EV fuelling station (b) unit casing; (c) urban air filter unit

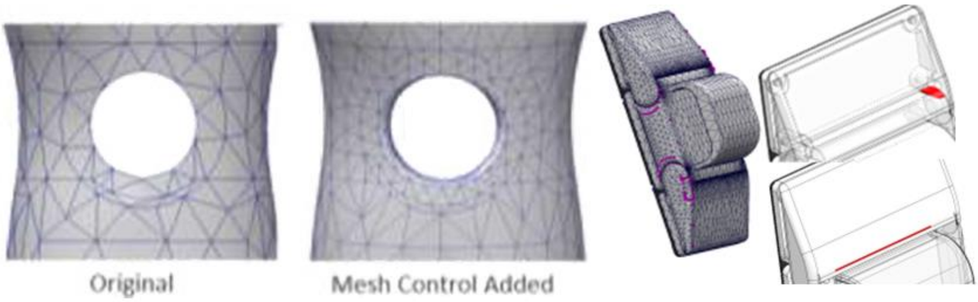

Figure 4. (a) interdental cleaning product mesh; (b) multi-part assembly

6.4 Validating and using FEA results for design impact

In the year 3 Engineering Design module students first learn to execute FEA to solve familiar 2D beam bending problems. Each problem is solved using formula alongside FEA, aiming to build confidence and emphasise a practice of checking and validating computer studies. This practice has been somewhat lost 2 years later with only 27% (6) of cohort 1 and 38% (9) of cohort 2 showing validating calculations in project work. Factors of Safety (FoS) derived from stress results are typically the most practical quantities for design and 50% and 65% of each cohort utilised FoS correctly. The best examples discussed results clearly in reports, highlighting key values (Figure 5b) and maximum stress locations (Figure 5c) in figures. However, there was a tendency for many to leave results as screenshots, too small to read (Figure 5a), with no design changes and 30% (6-7) of each cohort highlighted less useful strain results without any interpretation. In contrast figure 6 shows real design changes from iterative analysis.

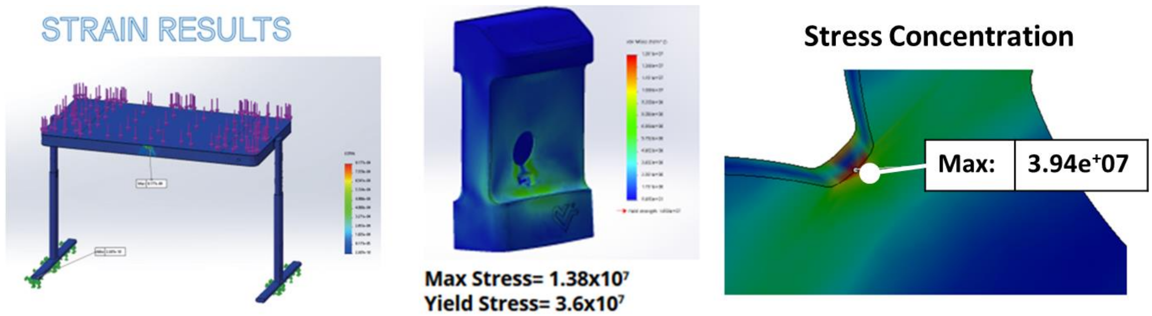

Figure 5.(a) home working desk; (b) defibrillator casing; (c) carry system for mountain bikes

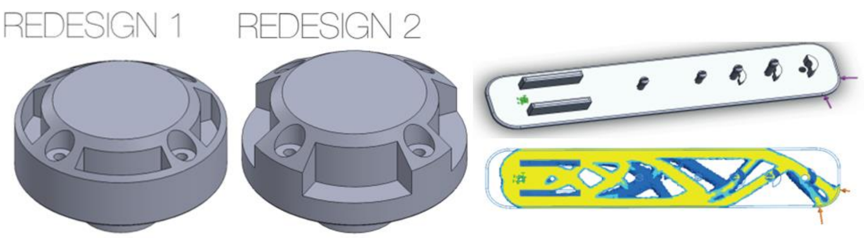

Figure 6. (a) lawn mower safety device (b) home daphnia cultivation device

7 DISCUSSION, LIMITATIONS AND CONCLUSIONS

The overall profile of the cohorts does not suggest that the FEA "good practice" workshop made a significant impact in the project work of cohort 1. Where a high proportion of cohort 1 included FEA, it is difficult to conclude that the slightly higher uptake in cohort 2 was due to the limited access to the university labs (often physical prototyping was achieved too despite this).

The growth in use of the "drop test" is not linked to any new timetabled initiative, but it was presented in the Integrating Project 3 for both cohorts. This may be one outcome of students' looking for virtual testing options following restricted access to the workshops.

Topology studies appear to have wide application. There is a significant opportunity for promoting the use of CAD analysis for real design changes and therefore it seems reasonable to prioritise topology study for future syllabus and curriculum development work.

The relevance of fluid, thermal and fatigue studies will be project dependent. There were a number of more projects that could have utilised these e.g., a rowing machine was analysed for bending failure, but did not consider the repeated cyclic impact on some components. Buckling is relatively straight forward and often more relevant than bending, but not used. It is interesting that the software's ability to analyse parts for their ease of injection moulding has not been explicitly taught, but students are making use of this feature in considering the manufacturability of their product. Like topology study, this appears a priority for embedding in the future. Where many students are undertaking multiple study types on the same part, multiphysics approaches should also be considered in the future.

Study limitations include that analysis was completed by the author alone and excluded year 4 project submissions and a project cohort who did not take the Engineering Design class but often undertake FEA. There have also been recent developments of the content and approach to delivering FEA which has not been captured in this up stream analysis; live and video demonstrations of FEA concepts and opportunities to be certified as an 'FEA associate'.

The insights gained are discussed with focus on implications for future development of FEA teaching throughout the curriculum, with an overall aim for it to be used more often to push embodiment and detail design project phases forward and less often as an item on an assessment check list.

REFERENCES

[1] Meadwell, James, David Terris, and Peter Ford. A little knowledge is a dangerous thing?–Do BSc Product Design courses discourage collaboration?. *DS 83: Proceedings of the 18th International Conference on Engineering and Product Design Education (E&PDE16), Design Education: Collaboration and Cross-Disciplinarity, Aalborg, Denmark, 8th-9th September 2016*.

[2] Adams, Vince, and Abraham Askenazi. *Building better products with finite element analysis*, 1999 (OnWord Press, Santa Fe)

[3] Kurowski, Pawel. *Finite Element Analysis for Design Engineers. 2nd ed*. 2016 (Warrendale: SAE International, Web).

[4] Akin, John Edward. *Finite element analysis concepts: via SolidWorks*, 2010 (World Scientific, Singapore)

[5] Le, Xiaobin, Anthony William Duva, and Michael Jackson. The Balance of Theory, Simulation, and Projects for Mechanical Component Design Course. In *2014 ASEE Annual Conference & Exposition*, Indianapolis, Indiana, June 2014, pp. 24-1189.

[6] Reffeor, Wendy S. Using FEA as a Pedagogical Tool for Teaching Machine Component Design. In *2018 ASEE Annual Conference & Exposition*. Salt Lake City, June 2018.

[7] Bingham, Guy, Darren Southee, and Tom Page. An integrated approach for the teaching of mechanics and electronics in a design context. In *DS 76: Proceedings of E&PDE 2013, the 15th International Conference on Engineering and Product Design Education, Dublin, Ireland, September 2013*

[8] Clavijo, Andrés, Renzo Boccardo, and Raul Angel. Model Building in Machine Element Education. *DS 46: Proceedings of E&PDE 2008, the 10th International Conference on Engineering and Product Design Education, Barcelona, Spain, September 2008*, pp.

[9] Beger, Anna-Lena, Alex Brezing, and Jörg Feldhusen. "The potential of low cost topology optimization." DS 76: Proceedings of E&PDE 2013, the 15th International Conference on Engineering and Product Design Education, Dublin, Ireland, September 2013.