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EXPERIENCE IN THE USE OF ENGINEERING PRODUCT DESIGN PRINCIPLES TO EXTEND NOVICE ENGINEER CAPABILITY

P. Jiang, S. Lee and PRN. Childs

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1. Introduction

Engineering designers face increasing demands in order to meet the sophisticated and complex requirements inherent in developing solutions for modern competitive products and systems [see, for example, Bar-Yam 2004]. Graduating engineers benefit from a solid understanding of design processes and their application in various situations [Atman 1999]. The principal aim of engineering design teaching is to provide an educational experience for undergraduates that will help them develop skills, integrate and synthesize knowledge and improve capability to propose effective solutions for life-long, real world problems [see, for example, Atman 1996]. Based on many engineering courses the positive effects on teaching students engineering design is clear and evidence also shows that students improve their performance after learning the engineering design compared to freshman [Mullins 1996]. There are however continued demands from industry for engineering graduates with better design experience. More open-ended problems are suggested by [Holmquist 2010] for insertion into engineering science courses with regular consideration of the design process, citing American industry where engineering graduates has been weak in design. Students need to be able think originally and link engineering theory to real-world problems [see, for example, Habibi 2013].

Imperial College London has one of the world's leading Mechanical Engineering Departments, training future graduate engineers and engineering analysts. About 29 % of the students come from overseas with inherently different cultural backgrounds, with the largest representations from China, Malaysia, France and Germany [Imperial 2011]. In order to develop design skills, a series of projects are used through first three years of students' study [Childs and Robb 2010, Childs et al. 2010]. This paper presents the research and experience on students' capability of adopting engineering design principles by providing an analysis of one of their design projects in which students are required to design a cordless hand-tool associated with a major manufacturer. This project requires students applying their knowledge of functional attributes, QFD (quality functional deployment), product design specification (PDS), idea generation and decision making in engineering product design. In particular this paper focuses on analysis of dominant design aspects such as technical, aesthetic, economic, psychological and social function through the students' QFDs, application of brainstorming and other creativity tools in idea generation and application of IBIS (issue based information system) design rationale, in order to scrutinise which aspects of the design process have been influenced by these activities and to provide an indication of whether the students have acquired skills and understanding as a result. In the remainder of this section basic principle of technical terms mentioned above are presented.

1.1 Production Design Specification (PDS)

A product design specification (PDS) is typically fundamental to the design activity, which fully determines in detail what is required of a product before it is designed. A PDS can be dynamic rather than static. If the emerging design departs from the PDS as a result of a new insight, then the PDS can be revised, in consultation and with the agreement of the principle stakeholders. The absence of a PDS can result in designs that do not address the market requirement and a poor PDS is a common reason for unsuccessful designs [e.g. see Cooper 1986]. Good PDSs do not necessarily result in the best designs but they do however make the goal explicit. A standard pro-forma approach to the development of a PDS is provided by [Pugh 1990] with 32 primary criteria suggested.

1.2 Quality Function Deployment (QFD)

Similar to PDS, QFD represents a sophisticated approach to define a specification. It is a systematic approach providing clear awareness of customer needs coupled with a range of functions [Ciri 2008]. The aim is to help designers understand customer needs and plan a product to provide superior value [Crow 2013]. QFD can also be described as "an overall concept that provides a means of translating customer requirements into appropriate technical requirements for each stage of the product development process" [Macro 2010]. There are four stages of QFD, named Product planning, Design Deployment, Process Planning and Product planning, or QFD1, 2, 3 and 4 respectively. Each stage of QFD represents a more specific aspect of product requirements [Crow 2013]. Although [Olewnik 2005] stated that using quantitative decision support tool such as QFD is potentially flawed, in this cordless hand tool design task described here, QFD was still recommended to assist students to understand the product functions and specifications. They are required to complete the first two stages, in which technical requirements are determined to meet customer requirements and then transferred into significant design characteristics.

1.3 Issue Based Information System (IBIS)

IBIS was first proposed to support coordination and planning of political decision processes [Rittel 1970]. It has three main types of elements called issues, ideas and arguments. A range of software is available embodying IBIS principles including QuestMap, REMAP, DRed, DesignVue and Compendium. In an IBIS approach everything is organised by questions with a structure allowing the diagrammatic representation to grow indefinitely if necessary [Conklin 1989]. It is able to provide a record of the design and decision making processes for reviewing, providing references, support and argumentations.

2. The Cordless hand-tool project

The proposition for the student activity is that a hand-tool company is expanding UK/EU market and they are searching for new ideas and innovation design for new generations of hand-tools. The students' task is to conceive and develop a product with a new type of functional head, using engineering justification for their concepts and produce a detailed solid model for the design. The project was undertaken by individuals and a project report was required for the assessment of students' work.

The main parts list for the devices suggested is:

- Multiple part hand-held body
- Functional head
- Battery
- Switch module
- Motor
- Power transmission gearbox as appropriate
- Charger as appropriate

The handle, motor, switch, battery and charger can be sourced from two existing products. However, the hand-held body, functional head and power transmission system require detail design. Figure 1 illustrates the two existing product models (Isio and ASB trimmer) and a selection of the designs developed by students.

Figure 1 Two current product models (Top) and some students' novel designs

The assessment and grade of students' work covers:

- A formal product design specification (PDS) using QFD1 and 2
- Conceptual ideas and evaluation
- Detail design of the product, including casing, transmission system and functional head
- Solid models
- Design for manufacture consideration
- Cost analysis

Related information was provided to students, helping them with the project flow, for example, QFD methodology, IBIS chart guidance, analysis and selection procedures for power and machine elements such as motors, batteries, and gears. It is suggested that since the company does not self-manufacture components, stock items could be chosen. The Total Design Core [Pugh 1990] was adopted in this project as a standard process for consideration by the students in their work, consisting of iterative

phases of market research, specification, conceptual design, detail design, manufacturing and marketing. The Total Design Core provides a framework which novice undergraduate engineers can follow, especially when they have little experience of where to start. By brief researching of the hand tool market, students were able to analyse products already in the marketplace, address their shortcomings and discover potential opportunities and improvements. The project is assessed by means of a report.

3. Design analysis

In order to analyse the students' work in more detail, a spreadsheet was established recording all 200 students' design activities, for the year concerned, containing key information such as product functions, design flow, concept generation, QFD1 and 2, functional head and product components design. Using this data, each student's design activity through their design can be located quickly. This database also provides comparisons between students' performance associated with certain activities such as QFDs and creativity tool employment. The figures and charts in this section provide the summary statistical analysis of students' designs with different focuses, for instance, dominant design aspects chosen by students and their performance on QFD employment. Based on these results the effectiveness of using the engineering product design case study to extend students' design capability is explored.

From the marked reports 76% of the students scored 60+ in the assessment, only 6% of them failed, with the low failure rate compatible with experience on project based learning. In 60 of the reports, all the students completed all the tasks requested to a high and convincing standard to the markers satisfaction that included a moderation process.

By addressing the importance of different product functions in students' product design specification, the dominant design aspects and design driving factors can be determined. This is achieved by calculating the absolute importance of different aspects in the students' QFD1. Figure 2 indicates that more than half of the students have chosen technical functions to be the dominant design factor, which means they chose technical functions of the product as a basis of redesign or new product development. This phenomenon might be expected since technical functions of an engineering product are generally referred to as product functions [Aurisicchio 2011]. Also in general, the main objective of hand tools when consumer purchases them might be anticipated to fulfil the need for being a tool. For example customers buying a cordless tree branch trimmer might normally be associated with when they have the need to cut branches. In contrast, 3% of the students have chosen an economic aspect. In industry, cost is crucial to engineers and designers since it is directly related to profitability [Crilly 2010]. Having this few students having addressed this issue may not be that surprising since novice undergraduate student engineers are not likely to have much experience on real industry problems. They will instead learn to take economic design aspects into consideration as they become more experienced. A judgement on whether technical or other functional attributes should be dominant design factors is not being made here. Instead the students' decisions are being evaluated, to see the outcome of their work with different focuses, and thereby provide some insight into novice engineers' design behaviour, and their acquisition of the materials presented in the course. Students having determined their design dominant aspects might be expected to see these fulfilled in their final designs suitably addressing the customer requirements. This was indeed the case for the majority, but with some issues which will be discussed later in this section. It should be noted that 5% of the students, did not submit their QFD charts. This exposes an issue that a small portion of students may not have understood the design process and the importance of PDS in engineering design. As stated before, absence of the PDS can lead to unsuccessful designs that fail to meet customer requirements. This issue suggests more intensive and targeted training is needed on the acquisition of design knowledge and PDS development skills among students.

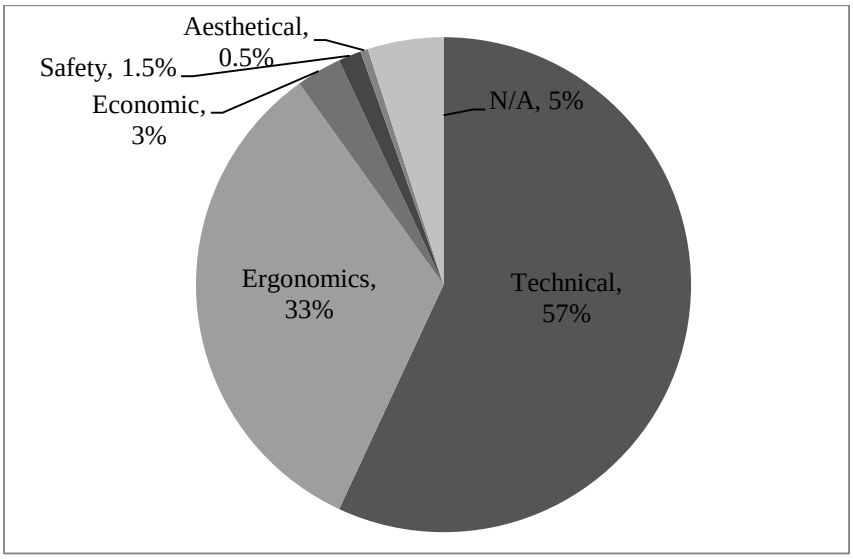

Figure 2 Dominant design aspects identified from customer requirements in QFD 1

Students were encouraged to use creativity tools such as brainstorming and morphological analysis helping them with idea generation. Figure 3 shows the percentage of students that have evidently used brainstorming for generation of functional and design concepts. Functional concept described here represents the main function of the hand tool and design concept stands for different hand tool designs regard to a same main tool function. The data indicates that among the students who have only one idea reported, over 90% of them did not use brainstorming in both functional and design concepts generation. In contrast with these students, in the group of students who have generated and reported more than three concepts, over 70% of them have used brainstorming to help devise ideas. The analysis suggests the value of creativity tools in conceptual idea generation, with the percentage of students who have used brainstorming rises with the increase in concepts generated. Creativity tools such as brainstorming, particularly if facilitated or evidently following a divergent and convergent process, can aid problem exploration, idea generation and concept evaluation. Despite the quality of an initial concept, it is still important to generate as many ideas as possible, within the constraints of resources available, since as more ideas are generated, the more likely a better solution will be achieved [Thompson 1999]. Once the students have generated different ideas and concepts, they need to evaluate them by providing design rationale and making decisions.

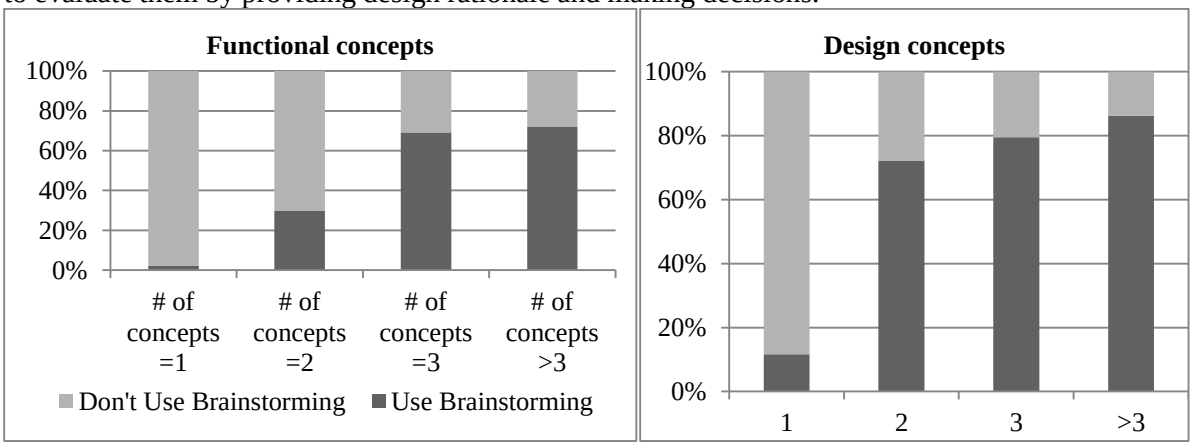

Figure 3 Influences on number of functional and design concept generated of employing Brainstorming

Data given in Figure 4 illustrates the students' performance on design rationale and their accompanying exploration of system design, choices and reasons for these [see MacLean 1989]. In engineering design, it is essential for designers and engineers to understand the reason behind a decision. This provides traceability in the event of issues, as well as a record to explore if

opportunities for new markets and products emerge. Design rationale fulfils this since it can include not only the reason behind a design decision but also the justification for it, other alternatives considered, the compromise made, and the argumentation leading to a decision [Lee 1997]. As a hierarchically web linked structured database, IBIS is able to manage design related information around issues [Cao 1999], which enables it being a suitable approach to provide design rationale for this project. Students were suggested to use IBIS to record their design activities and decision making process, including the selection hand tool main function, tool components selection and design concepts evaluation. Figure 4 indicates that around half of students have used IBIS to provide engineering justifications while quite a number of them made decision without any evidence. Most students have provided reasonable justifications and support for their hand tool function selection and components selection, which has shown their good consideration on design rationale in these aspects. In an example of students' work shown in Figure 5, two main issues were offered with several solutions proposed around each of them with justifications. Decisions were made based on argumentations of each potential solution, indicated by a hand-shaking node (for detail see Figure 5).

In contrast, the result having over 30 % of students who did not provide any evidence supporting their decisions is disappointing. Without justification and argumentation on decisions, clients, report markers in this case, were uncertain how concepts were selected and why others were eliminated. Even for novice engineers themselves, it is crucial that the justification and argumentation associated with decisions are recorded, so even if the final design fails client's demands, they can go back, review each decision they made, make adjustments and start over. Moreover, a record of design activities can also enable designers to improve their product from any stage where they made decisions. Therefore, helping students to develop a deeper understanding on the significance of design rationale represents another feature to be improved for this cohort and future projects.

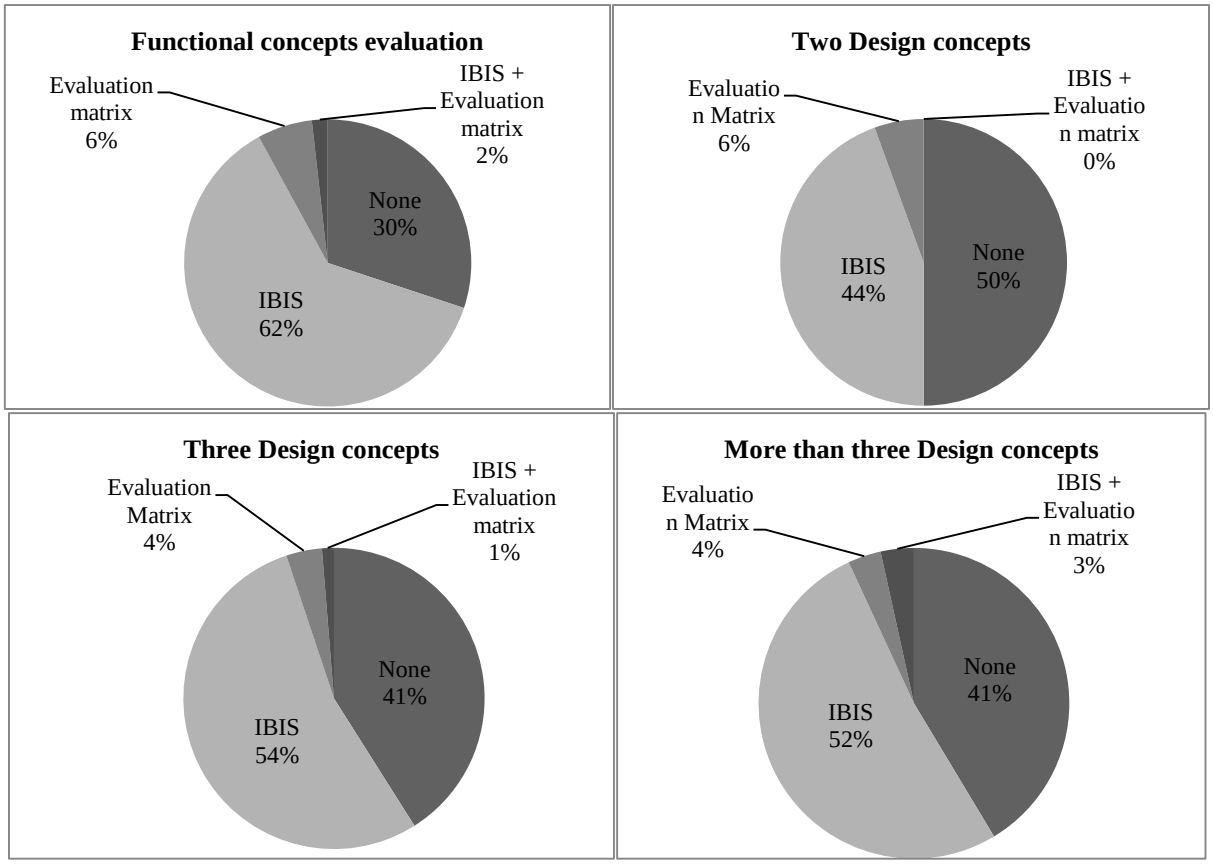

Figure 4 Percentage of evaluation methods employment in students' functional and different number of design concepts

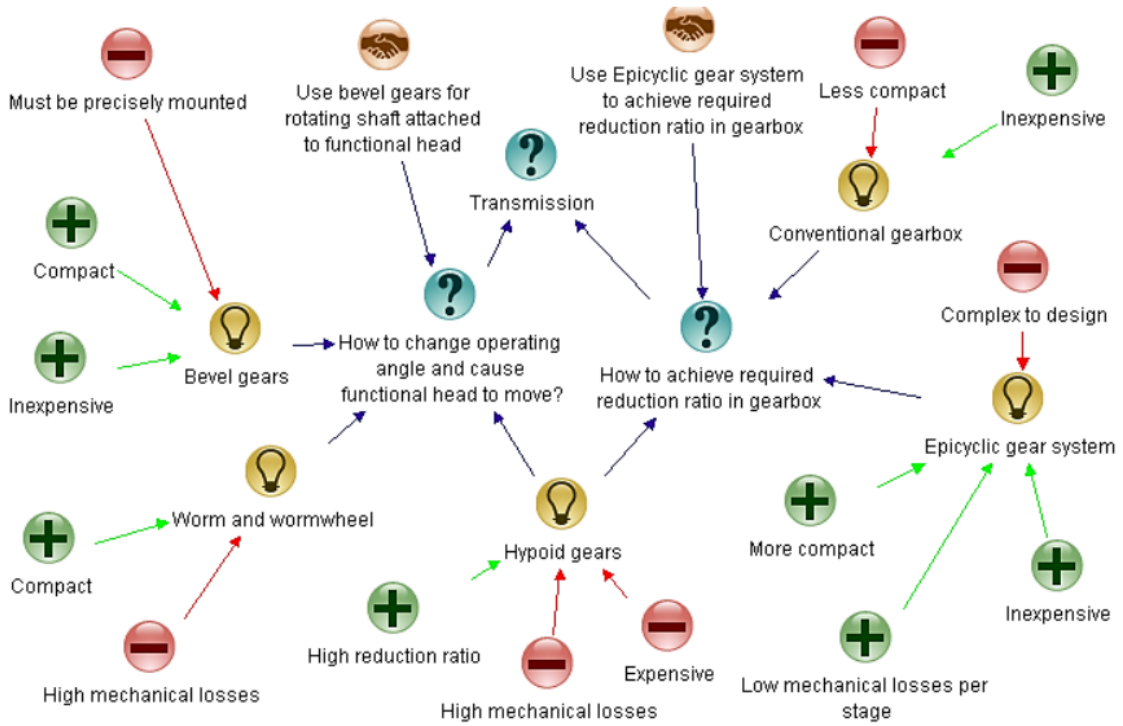

Figure 5 An example of gear transmission considerations and idea evaluation

Various shortcomings in the students' reports arising from the analysis are highlighted in Figure 6, 7 and 8. It was found that only 29% of the students have completed QFD1 and 2 correctly from the data shown in Figure 7. The calculation and conveyance of product function importance in QFD1 and 2 was found to be the most popular issue students had. QFD2 aims to determine product parts attributes which will fulfil the product functions defined in QFD1 with priorities. Engineers and designers determine the product function customer care the most based on their absolute importance, by multiplying product attributes importance and their relationships with product functions together. However, nearly half of the students simply duplicated the product functions from QFD1 to 2 directly and rated them once more. The product functions importance became judged by engineers subjectively instead of customers, which may cause misleading of the design focus and eventually fail to fulfil customer expectations. For a hand tool, its functions are normally relatively simple and straightforward, but this issue may cause complete project failure in complex product design with a range of function requirements. The result exposes a lack of understanding of QFD, suggesting improvements are necessary on QFD skills provision, acquirement and utilisation.

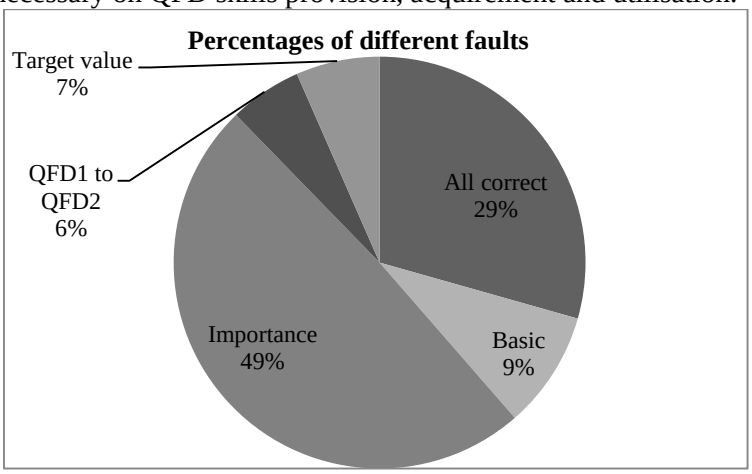

Figure 6 Different type of mistakes in QFDs indicated among students

Another issue implied from the analysis is the insufficient influence of product specification on the outcome of students' designs. Figure 7 indicates excluding functional head design, over 75% of the students have not managed to consider the design requirement/specification stated in QFDs into their detail design, which means QFDs they established before have little impact on their designs. This is significant since it affects the quality of students' designs directly. For instance, one of the student's design specifications stated a lightweight requirement for transmission gears in order to maintaining the tool's overall weight, however the gear stress analysis later recommended metal gears since lightweight gear material such as nylon would not satisfy the strength constraint indicating that the design has been diverted from the original specification, failed to meet the lightweight requirement. Although half of the students have met the functional head specification successfully, this still suggests further adjustments and improvements to enhancing students' capability on employing product design specification. Another reason presumed is students' insufficient attention on product components design other than the functional head. Other components are equally important as the functional head, together they compose to a complete product. It seems that students mainly focused on the design of functional head base on the specification, and neglected the requirements on other components stated. This issue can also be seen from the analysis in Figure 8 that a considerable proportion of students did not take shaft and bearing design into consideration. Students were asked to design the functional head and appropriate transmission systems, and most of them have achieved the goal successfully with new functional head (See Figure 8). In contrast quite a few students failed to consider the alteration in shaft and bearing design along with the change in the functional head and transmission system. This suggests a lack of consideration of the design from an integrated point of view. Therefore, better awareness and practice on the design of other tool components is suggested to enhance students' design abilities.

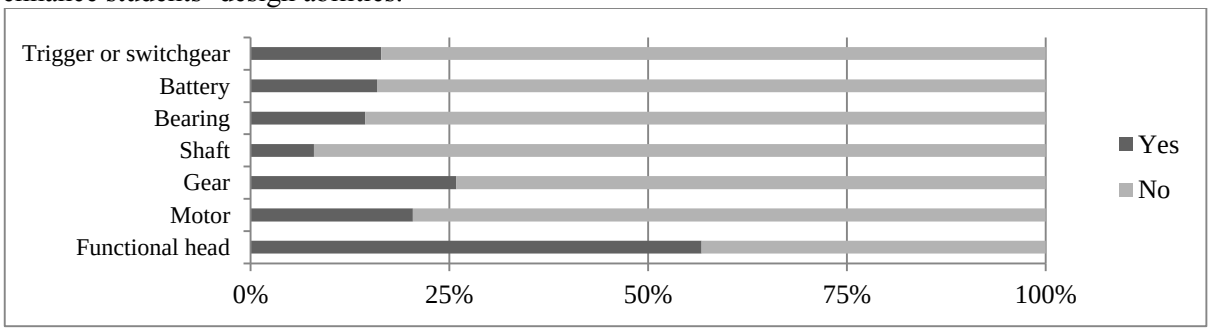

Figure 7 Components design according to product design specification

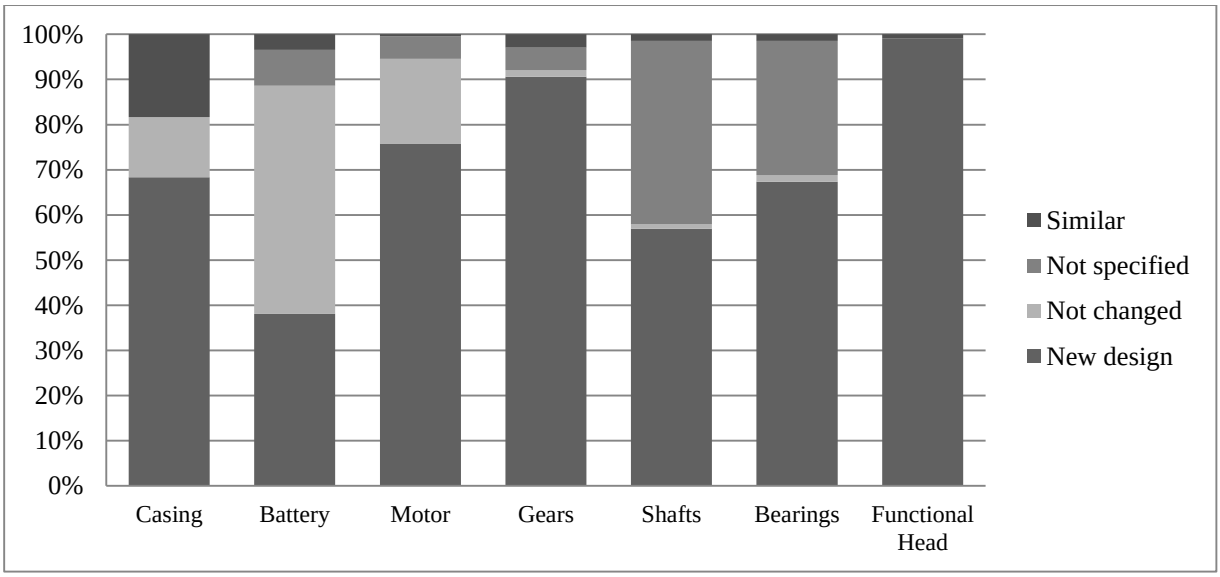

Figure 8 Component designs categorized by sub-systems compare to original designs (The order of filled column is in the same order of the legend entries)

4. Conclusions

An analysis has been made of the outcome of an engineering product design task undertaken by a group of over 200 second year integrated masters MEng undergraduate students. In particular students' consideration on product functional attributes through their product design specifications has been examined in order to see the influences of their consideration on the final design outcome, as well as their employment of creativity tools and design rationale in their design process.

The results indicate:

- Most novice undergraduates intend to treat technical attributes as design dominant factors and are capable of achieving it in their designs.
- The value of creativity tools in idea generation assisting novice undergraduates devise broader range of solutions.
- The significance of design rationale by providing engineers a record of design activities and argumentation behind a decision, for the worthy of future adjustment and improvements.
- A tendency for incorrect and incomplete employment of QFD1 and 2 as product design framework.
- Insufficient recognition of product specification significance and its role in the engineering design process.

The analysis suggested that:

- The cordless hand tool task provides a tangible engineering challenge for students to deliver development of engineering design knowledge and skills for novice engineering undergraduates.
- More intensive training on design thinking and skills focusing on specification and design rationale is necessary.
- In order to enhance the knowledge acquirement of students through case studies, modifications to the teaching approach are proposed. Instead of carrying out a complete report containing all features, students could be tasked to complete the project through stages, producing for example a product design specification using QFD1 and 2 which will be assessed individually near the beginning. Students will then be able to carry on based on the specifications with feedback. Splitting the project should be able to help students achieve their designs based on the understanding of work already accomplished.
- With the feedbacks of students' performance from each year, adjustments and improvements on the teaching structure and approach can be proposed, aiming to extend their engineering design capability in a more sophisticated manner.

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Mr Pingfei JIANG
Research Postgraduate
Imperial College London, Mechanical Engineering Department
South Kensington, London, UK
Pingfei.jiang10@imperial.ac.uk