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Design for Manufacture (DFM) within Professional Practice and its Relationship to Design Education

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Abstract

This research set out to assess the importance of Design for Manufacture (DFM) within the industrial design process, understanding how it is taught, and comparing this to the requirements of professional practice. A mixed methods approach was applied in, collecting a combination of both quantitative and qualitative data through two questionnaires. The first questionnaire was directed at current and graduate students from the Industrial Design (ID) and Product Design (PD) courses at Loughborough Design School. The second questionnaire targeted design companies that had previously employed Loughborough students in either placement or graduate roles. The results of the two questionnaires were then analysed individually before comparing a selection of directly corresponding results.

The results from the primary research showed that both students and companies agreed that DFM was a key skill utilised within professional practice. In both cases, DFM was regarded as more important than sketching and sketch rendering, supporting findings within the literature review that the role of the designer has changed. It was discovered that the main benefit of a professional designer implicating DFM during the design process was an overall reduction in cost. It may be concluded that, although the teaching of DFM at Loughborough Design School supplied the students with some knowledge, it does not entirely meet the requirements for professional design practice.

Key words

design for manufacture, professional practice, design education

Introduction

It has been well recognised that the role of the designer is changing (Gemser & Leenders, 2000). However, it is not yet fully understood whether this change is reflected within design education. Although there are many skills that the designers require for their role (Hurn, 2006), it has been found that one of the most important areas within the design industry, is Design for Manufacture.

Design for Manufacture (DFM) is the relationship between design and manufacture in order to improve performance and quality whilst reducing cost (Corbett, Dooner, Meleka, & Pym, 1991). This research will use this working definition, to find out whether DFM is being taught sufficiently within undergraduate education to prepare students for professional practice.

The aim of this work was to assess the importance of Design for Manufacture (DFM) within professional practice, comparing how it is taught within education to prepare students for industry. In order to fulfil this aim, the following objectives were achieved: a review of literature on the role of DFM within both professional practice and education; an investigation into the understanding of students' knowledge of the importance of DFM; an investigation of the skills that design-based companies require from placement or graduate students; a comparison of the opinions of the students and companies to fully understand if the teaching of DFM is relevant to professional practice.

Design For Manufacture (DFM)

'Industrial Design is the professional service of creating products and systems that optimize function, value and appearance for the mutual benefit of user and manufacturer' (IDSA, 2016). It is often mistakenly assumed that an industrial designer is only focused on the aesthetics of a product (Norman, 2011), however, recently it has become apparent that designers need to have an understanding of engineering, production processes, Computer Aided Design (CAD), as well as the more typical design techniques (Nichols, 2013). This is backed up by Gemser and Leenders (2000) who state that the role of the industrial designer focuses not only on aesthetics but on other areas, such as ease of manufacture, ergonomics and efficient use of materials. Initially, it was confirmed that the role of the designer had changed, progressing from the traditional role, who solely focussed on craft based skills: sketching, modelling, detailing and rendering (McCullagh, 2010), to the newly developing role where additional knowledge of engineering based skills such as DFM and CAD are required. Due to the varying nature of the design process, Baxter's (1995, pp. 261-265) three stage theory - concept stage, design development and detail design - was selected because of its simplicity. Next, the term DFM was defined as the combination of both design and manufacture working simultaneously to improve cost, quality, lead times and performance (Susman, 1992).

Previous research has established that a recent increased investment of industrial design in new product development has led to the financial success of companies such as Apple and Phillips (Gemser & Leenders, 2000). This is because an industrial designer has the ability to improve product appeal and build brands, whilst minimizing manufacturing costs (Ulrich & Eppinger, 2003). Research has highlighted that Design for Manufacture (DFM) should be part of the modern designer's tool kit. Susman (1992,) states that DFM, within new product development, is the combination of design and manufacture working simultaneously to improve cost, quality, lead time and performance. It is established, from a variety of studies, that one of the best ways to minimise manufacturing costs and reduce the labour-intensive assembly costs in new product development, is to apply product design techniques (Dewhurst & Boothroyd, 2003).

Well executed DFM should lower the cost of manufacture without detriment to the product quality. It also diminishes the lead times, as it will reduce the number of iterations from the industrial designer, which would otherwise have implications to the economic cost. It can play an important part in the commercial success of a product (Ulrich & Eppinger, 2003). Langowitz (1987) clarified that traditionally it was thought that design and manufacturing should not work together and that there should be clear definitions between the two. This has been described by Boothroyd (1994) as an 'over the wall' approach. A designer completes their work, and passes it on to manufacturers, who then deal with engineering issues, having had no input at the design stage. A financial cost may be incurred through this lack of simultaneous approach as manufacturing and assembly issues commonly arise. Furthermore, it has been discovered that by considering DFM early in the design process, the number of parts, fixings, manufacturing operations and assembly times can be reduced. The costs of these changes are highlighted in figures 1 and 2. Both diagrams show that the cost of making a design change increases as the design process progresses. Evidence shows it is more efficient to make changes at the beginning of the design timeline, as this is where the most influential decisions on manufacturing costs are made, but the smallest amount of investment is required (Magrab, 1997). This is confirmed in a study by Rolls-Royce that found 'design determines 80% of the final production costs of 2000 components' within their vehicles (Corbett, et al., 1991). Figures 1 and 2 depict the benefits of DFM within the design process.

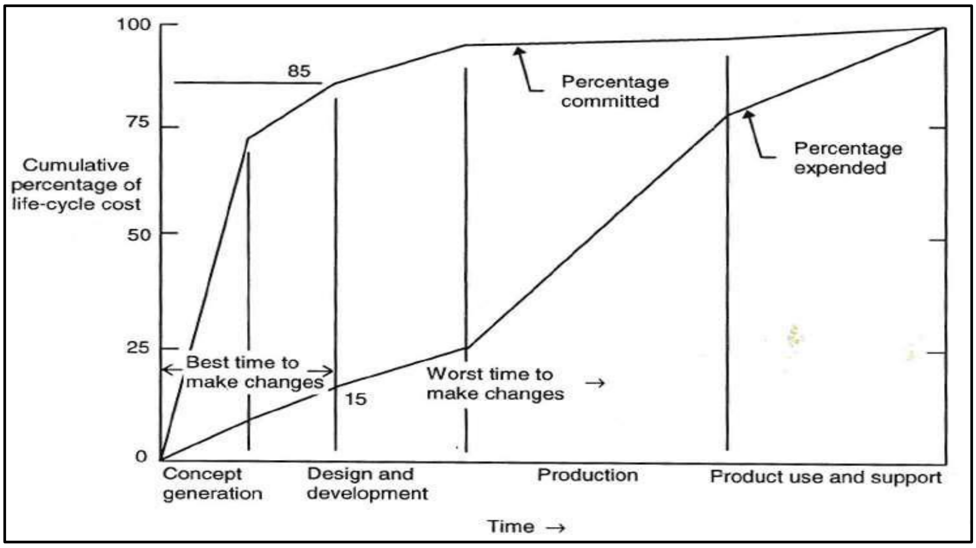

Figure 1. Cumulative product life cycle costs at the various stages of the product realization process (Magrab, 1997)

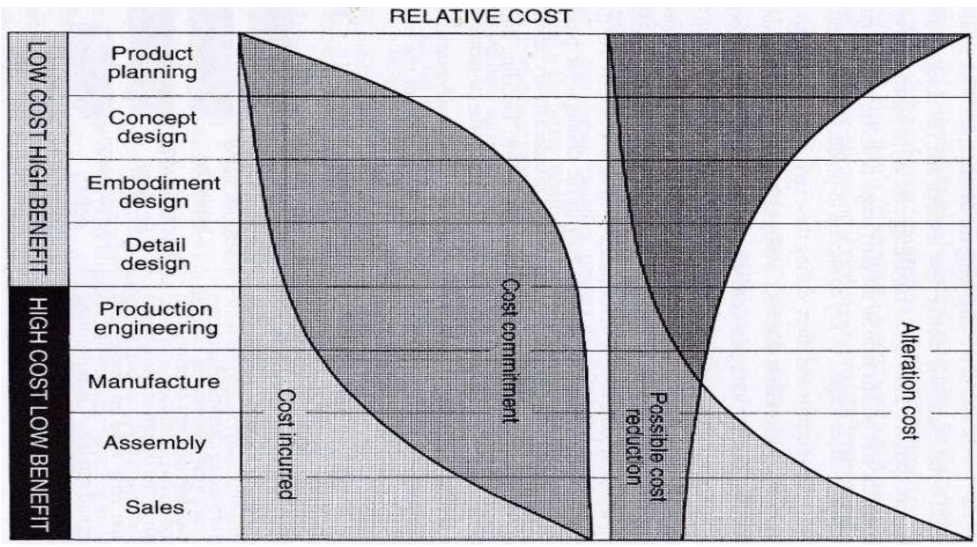

Figure 2 - Costs and benefits of different design stages (Baxter, 1995)

Ulrich and Eppinger (2003, p. 196) state that the design process is not common to all practices and vary from each firm, or even project. They outline a generalised industrial design process into 6 stages: investigation of customer needs, conceptualisation, preliminary refinement, further refinement and final concept selection, control drawings and, finally, coordination with engineering, manufacturing and vendors. Baxter (1995, pp. 261-265), however, simplifies the design process in just 3 stages: concept design, embodiment design/design development and detail design. He also explains how these stages overlap with one another with no clear finish or end.

A further body of work also expresses the design process in three stages: explorative phase, transformation phase and convergence (Lal, Gupta & Venkata Reddy, 2005), which are directly comparable to Baxter's theory. Therefore, this research will use the three stages defined by Baxter (concept design, design development and detail design) to explore DFM's role within the design process. Thus far, the research explored has highlighted the benefits of the industrial designer's application of DMF techniques early within the design process, to benefit new product development (Periyasamy, Sundaresan, and Natarajan, 2015). However, in reference to education, little has been published regarding the extent of students understanding of DFM, and how it can be applied to professional practice (Li, and Lockett, 2017).

The undergraduate teaching of Industrial or product design is a relatively new subject area, designers needing a broad range of skills from a number of disciplines (Hurn, 2016). McCullagh explains that the expanding scope of design means that craft techniques that designers are traditionally skilled in (sketching, modelling, detailing, rendering) have a lesser importance in the newly developing role of the designer. He goes on to suggest that the ignorance towards production techniques and industry dynamics leads to designers losing credibility (McCullagh, 2010), further suggesting the need to acknowledge the designer's changing role. It is therefore important that this change is also embraced within education (Favi, Germani, and Mandolini, 2016).

This study will focus on Loughborough Design School as the chosen educational model, in order to discover whether the teaching of DFM is sufficient for professional practice. At the Loughborough Design school (LDS), there two major undergraduate courses: Industrial Design and Technology BA (Hons) and Product Design and Technology BSc (Hons). The major difference between the two programs is that Product Design and Technology students are taught engineering based subjects (mechanics and electronics) whereas Industrial design and Technology students focus more heavily on the traditional design techniques (Bingham, Southee, & Page, 2015)). In the context of this research, an Industrial Designer (ID) is one that has taken part in the Industrial design and Technology BA course at LDS, whereas a product designer (PD) is one that has taken part in the Product Design and Technology course at LDS. The term designer will refer to the general population of industrial and product designers. Figure 3 outlines the basis of what is involved at each stage.

What stage?	What design thinking?	For example?
Concept design	Design principles for the whole product.	Hand-held or desk-top adhesive tape dispenser?
	Preliminary ideas on embodiment design for the whole product.	Main body of moulded plastic or cast metal?
Embodiment design	Design principles for product components.	Alternative general forms and functions for tape holder.
	Embodiment design of product components.	Specific form, function material and process for components.
	Preliminary ideas on detail design for product components.	Simple two-part injection mould tool?
Detail design	Design principles for detailing product components.	Increase wall thickness or add ribs or bosses?
	Detail design of product components.	Full technical drawings and product specification.

Figure 3 - Stages of the Design Process (Baxter, 1995)

Both ID and PD students have the option of a four year 'sandwich' course that provides the opportunity to work within a company, gaining professional experience. This is understood as a placement year in which 83% of students took part within 2016 (Loughborough Design School, 2017).

For the past fifteen years, students at LDS on both ID and PD courses have taken part in an injection moulding project which teaches applied DFM techniques. This gives the students an opportunity to implement DFM skills whilst designing a plastic widget, therefore, introducing them to real world design issues. Initial feedback from students, companies and examiners has been positive (Marshal & Page, 2016). However, there is limited understanding of the extent of this success, for example: would the course allow the designer to integrate into a design team with little or no further experience in DFM. Through further investigation, it appears that the commercial importance of DFM has not been explored (Betancur-Muñoz, Osorio-Gómez, Martínez-Cadavid, and Duque-Lombana, 2014).

Methodology

The literature review has highlighted the benefits of DFM within the design process, specifically highlighting its advantages when applied in industry. However, it was also acknowledged that it is not yet understood whether these advantages have been fully integrated within design education. Therefore, primary research has been undertaken to further understand the benefits and effectiveness of DFM with both the ID and PD course at Loughborough Design School.

A mixed methodology approach has been used. The method, which has recently increased in popularity, combines both qualitative and quantitative data (Robson & McCartan, 2015). The quantitative data will provide statistical results, whereas the qualitative data will provide further understanding (Barbour, 2014). This has been achieved by conducting two questionnaires: one directed at undergraduate or graduate students from the ID or PD course at LDS and the other directed at companies that employ LDS students as either placements or graduates. The two viewpoints allowed for data to be compared in order to validate the results. A questionnaire has been used to get the widest range of viewpoints, creating a more accurate representation of the population, as well as being a cost-effective method (Davies & Hughes, 2014).

The quantitative data will be amassed from a series of questions providing nominal and ordinal data. The nominal data will create a series of categories in which the ordinal data can be subdivided. This ordinal data will give the participants a chance to provide their opinion using scales or multiple choice answers. Any questions that require a scalar response will have a measure of '1' to '5', where the positive and negative ends of the scale have been kept consistent to avoid confusion for the participants, as well as making the results easier to decipher. This data has been represented graphically to prevent a 'lengthy and cumbersome' text based paper (Walliman, 2014). Furthermore, some data points will be analysed using mean values to determine overriding results from the spread of data.

The qualitative data will arise from a series of open ended questions. These responses will be analysed by grouping words and phrases into trends so that reoccurring themes can be identified. In addition, qualitative research unpicks and makes visible particular variables, providing a 'fuller picture' of the results (Barbour, 2014). The questionnaires took the form of an online survey due to the simplicity of setting up and the ease of sending out and collecting the results. The student questionnaire was sent out via email as well as being shared on a social media platform. The company questionnaire was emailed directly to the participant or passed on via current placement students.

The limitations of a questionnaire must be considered. It cannot be guaranteed that the participants will answer honestly. By targeting two separate parties and comparing the results, hopefully it will highlight and enable the removal of any anomalies. Furthermore, the title of the surveys suggests focus toward DFM, which may subconsciously bias the results. A blind questionnaire asking similar questions would be useful to validate the data. When analysing the results, each questionnaire was explored individually before comparing answers. A selection of the questions in both the student and company questionnaires are directly comparable and these have been analysed together to highlight any contradictory or similar opinions.

Results

Student Questionnaire

A total of 46 students took part in the student questionnaire. All the students that took part were graduates or undergraduates from the Industrial Design or Product Design courses at Loughborough Design School.

Nominal Data

The questionnaire directed at students had an almost even representation from the ID course (47.8%) and PD course (52.2%). This meant that even comparisons could be made between the two categories. The proportion of graduate to undergraduate however was uneven, with 73.9% the responses coming from Undergraduate students and only 26.1% from graduates. To overcome this deficit, the results will be looked at proportionally to each category rather than nominally.

The final question providing nominal data, wanted to find what professional experience the designers had undertaken. The options given were Graduate job, Placement year, Both or None. The data showed that 92.3% of the questionnaire population had at least taken part in a Placement year. Of the graduate students, 75% had experience from both a placement and a graduate job. From the population of undergraduate students, 91% had taken part in a placement year. Only 8.7% had no work experience at all, whom were all undergraduate students.

Areas of Importance and Improvements

This section of the questionnaire gave the participants checkbox style questions. Primarily, the students were asked to select the four skills that were most relevant for professional practice. The data shows a strong bias towards Computer Aided Design (CAD) with 93.5% of all the students seeing this as a priority. This was closely followed by DFM (76.1%), before sketching and sketch rendering (56.5%), and then visual 2D presentation (50%) (figure 4). Areas that were deemed noticeably less important were sustainable design (4.3%), marketing (13%), mechanics (15.2%) and electronics (4.3%).

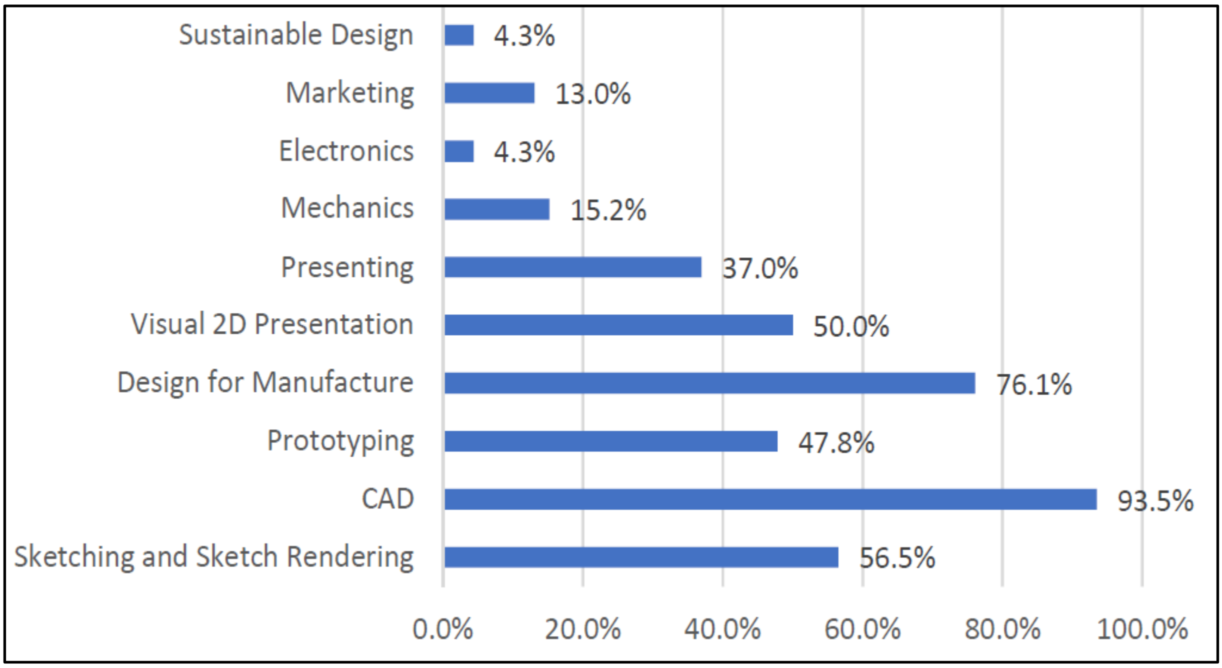

Figure 4: Selection of skills the students understood to be the most relevant to professional practice

After selecting the subject areas most relevant to professional practice, the students were asked to decide which of those areas LDS needed to improve. DFM was the most frequently suggested subject area with 65.2% selecting this answer (figure 5). Marketing was the second most popular answer (47.8%), followed by electronics, Visual 2D presentation and CAD, all with 37% of the population suggesting that these subject areas needed improvement. When comparing the different subject categories, graduate and undergraduate, ID and PD, there were no significant variances in the results.

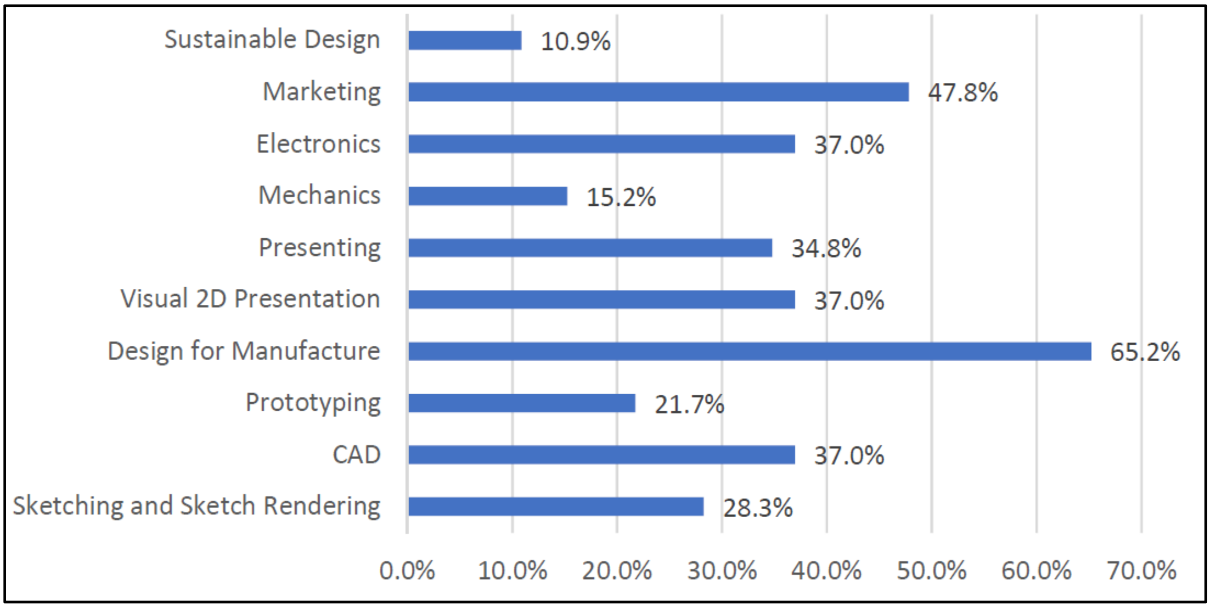

Figure 5: Areas of the LDS education that students feel needed improvement

DFM Teaching

The students were asked for their opinion as to whether they thought that LDS had improved upon their knowledge of DFM. The results showed that 41.3% agreed and 19.6% strongly agreed, evidencing that a majority felt that their knowledge of DFM had improved to some extent. When exploring the comparisons between ID and PD students, a greater proportion of ID students strongly agreed, whereas the PD students tended to agree with the previous statement. However, the differences between the results were not clear enough to make any decisive conclusion.

Subsequently, the participants that had worked in industry were asked if their knowledge of DFM learnt at LDS was sufficient for their graduate or placement role. This was gauged on a '1' to '5' scale, with '1' being strongly disagree and '5' being strongly agree. The results were relatively evenly distributed either side of the neutral answer ('3'), of which 38.1% selected. A total of 35.7% agreed or strongly agreed, whereas, 26.2% disagreed or strongly disagreed with the statement. When comparing the results of ID and PD students, there was some notable distinctions. PD students were more positive, with a mean result of '3.3', yet ID students were more negative, with a mean result of '2.6'.

The students were next asked to provide qualitative data discussing any differences between their university and professional understanding of DFM. Almost all the responses were in relation to the injection moulding project carried out at Loughborough Design School, in which students are asked to design a plastic widget. When analysing the data, the most common trends were the limited teaching of: cost, mass manufacturing techniques, and real world injection moulding knowledge.

The lack of real-world injection moulding knowledge was the most popular answer. This was due to the restricted teaching of moulding techniques that are essential for mass manufacturing within industry. It was also suggested that more knowledge on other mass manufacturing techniques should be provided. Furthermore, cost was a key element expressed by many of the participants as a vital part in professional practice but had not yet been considered within undergraduate education.

DFM Understanding

Many of the students claimed to 'always' consider DFM when they designed a new product (45.7%). 37% claimed that they 'often' considered DFM and 15.2% 'sometimes' considered it. Only one participant responded saying they rarely considered DFM when designing a new product. The results were broken down into subcategories. This found that most graduates would 'always' consider DFM, whereas undergraduates would 'often' consider it. Similarly, when comparing PD and ID students, it found that the PD students were more regularly considering DFM than ID students when designing a new product. However, there was less difference in these results than between graduate and undergraduate students.

Furthermore, a basic knowledge test, comprising of three questions, was included within the survey. The first question asked the participant to state three fundamental aspects of DFM which should be considered in the development of a new product. This question sought to assess whether the participant had a basic understanding of DFM. Out of those that answered the question (43 out of 46), all of them seemed to grasp a basic understanding. There were 6 different answers given, of which the most common was cost, with a response of 67%, followed by manufacturing method (58%) and thirdly material selection (47%).

Further to this, the students were asked to state at what stage in the design process they believed DFM should initially be considered. The participants were given three stages outlined by Baxter's theory on the design process: concept design, design development, detail design (Baxter, 1995). The data shows that 56.5% of participants believed that DFM should be considered at the second stage during design development. 32.6% of the population selected the concept design stage and only 10.9% selected detail design stage. The overall results were divided into groups to visually compare undergraduates and graduates. Graduates from the LDS believe that DFM should be considered at the initial concept design stage (58.3%). Whereas most undergraduates selected the second stage, design development. When comparing ID and PD, there was almost no difference.

Subsequently, the student's understanding was tested further by enquiring: at what stage is the largest proportion of manufacturing costs determined? Over half the participants selected design development, 30.4% selected detail design, and only 17.4% chose concept design. Once again comparing graduate to undergraduate students, it was clear that the graduates had a better understanding of applying DFM techniques earlier in the design process. 41.7% of graduates selected the concept stage compared to 8.8% of undergraduates.

Preparation for Professional practice

Participants expressed views on whether the ID and PD courses at LDS need to improve the teaching to prepare students for professional practice. 45.6% of students either agreed or strongly agreed that the LDS teaching needed to improvement compared to 19.5% who disagreed or strongly disagreed. 34.8% of the population had a neutral opinion.

Those who thought that the teaching of DFM within the LDS needed improvement were asked to give examples of how they thought it could be improved. 40% of the student population offered a suggestion. Of this 40%, 75% expressed the need for further teaching of DFM, specifically looking at more 'real world' solutions. This included: looking at well-designed existing products and understanding how these parts were moulded and produced on a mass manufacturing scale. Multiple responses also suggested that the weighting towards visual techniques did not correspond with the amount these skills were used in industry.

Company Questionnaire

20 companies, who had previously employed LDS students as either placement students or graduate employees, completed this questionnaire.

Firstly, it was important to understand the companies' views on their respective LDS student employee's performance, before further assessing details about specific knowledge regarding DFM. The results were unanimously positive with the entire population of the survey agreeing it had been a success to employ LDS students as either placements or graduates.

Areas of Importance and Improvements

Similarly to the student questionnaire, the companies were asked to choose the four most favoured skills from a placement or graduate. The majority (94.4%) of the population of companies selected CAD as the most favoured skill. This was followed by DFM (72.2%), sketching and rendering (66.7%) and both prototyping and visual 2D presentation with 55.6% (figure 6).

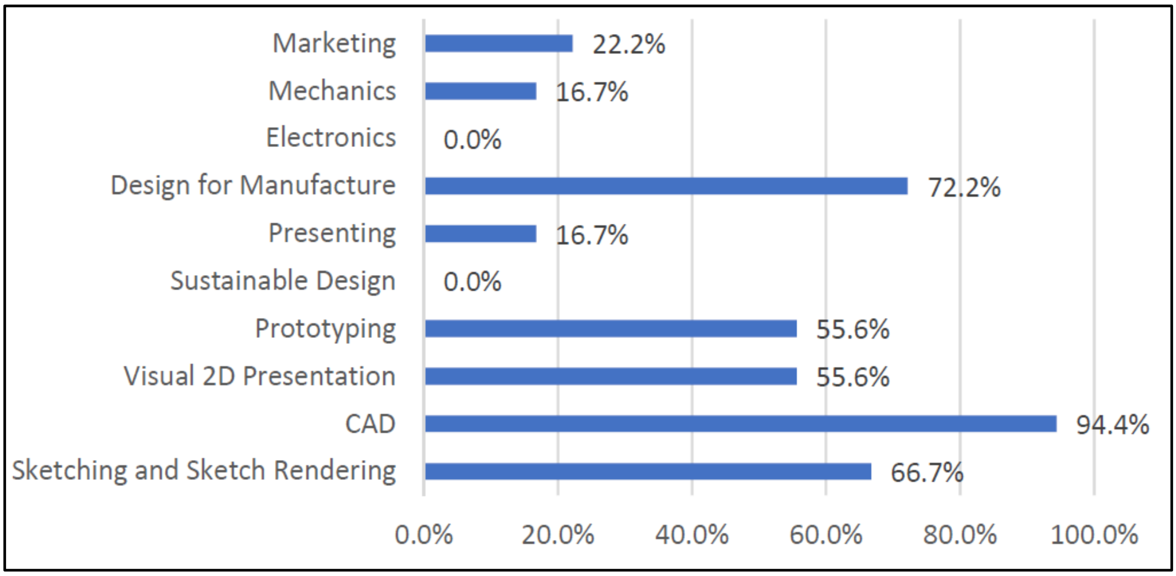

Figure 6: Companies selection of the most favoured skills from LDS students.

According to the companies, the areas that needed the most improvement were DFM and CAD with both being selected by 61.1%. The next most common answer was visual 2D presentation (38.9%) followed by prototyping (33.3%).

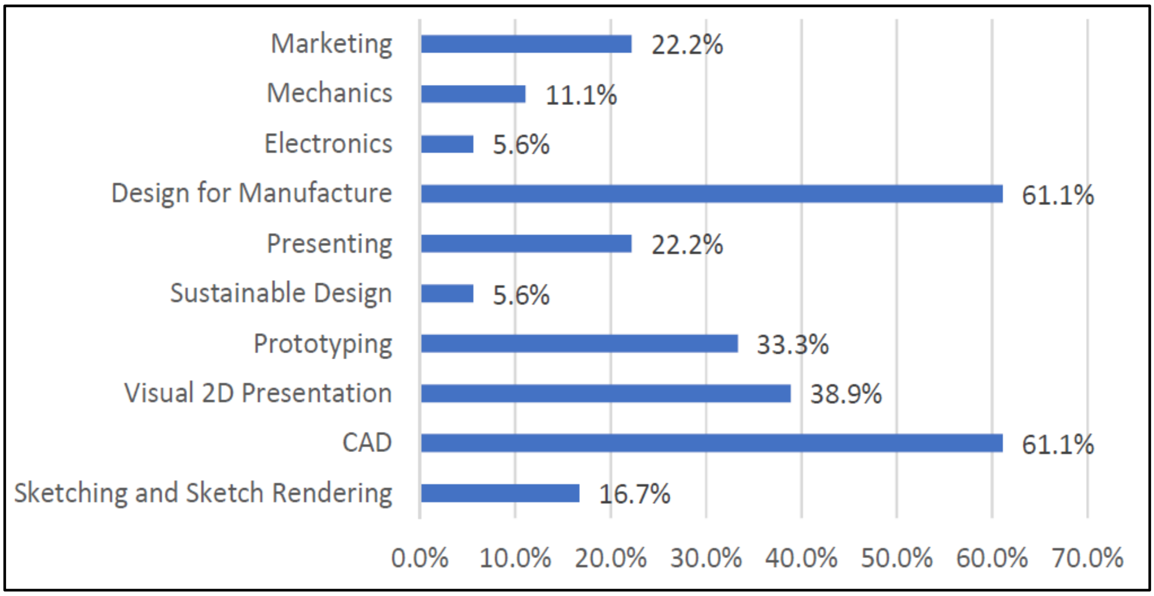

Figure 7: Areas in which companies believe that students need to improve upon.

DFM within Professional Practice

Corresponding with the student survey, the companies were asked to select when they considered DFM within their design work. Yet again, using Baxter's terms: concept design, design development, detail design, three quarters of the companies considered DFM at the concept design stage of the design process. The remaining 26.3% considered DFM at the design development stage, whilst no company selected detail design.

With regard to the which role within the company makes the biggest contribution to DFM. More than half of the participant companies selected 'in house industrial designers' as the role that makes the largest contribution to the DFM of a new product. 26.3% chose 'in house design engineers' and 10.5% outsourced their DFM needs.

Exactly half of the companies surveyed explained that they 'always' expose their placements or graduates to DFM. 38.9% claimed they often exposed their students and 11.1% 'sometimes' expose their students to DFM. None of the companies selected 'rarely' or 'never'. From this data, we can understand that 88.9% of students were exposed to some level of DFM when employed.

DFM Teaching

In relation to the companies' opinions on whether LDS students had a good general knowledge of DFM. A large number of responses (66.7%) had a neutral view, neither agreeing nor disagreeing. A small number agreed (11.1%) and similarly a small number disagreed (16.7%). Assessing whether the employee had enough knowledge to carry out their role within the company, the results were slightly more positive. Once more, a large proportion (52.6%) had a neutral opinion, however, 36.9% agreed that the students did have enough understanding for their role, whilst only 10.5% disagreed.

Building on this information, the companies were asked to point out any differences between the teaching of DFM at LDS compared to the necessary skills required within professional practice. When analysing the responses, two key themes arose: lack of knowledge of mass manufacturing techniques, and an 'understandable lack of experience'. These two themes encompassed almost all the responses, with some adding more focused suggestions, such as the need to improve knowledge of CAD and increasing understanding of cost.

Comparisons with other universities

The final quantitative question looked to compare LDS students to other university design students to understand whether there was any difference between their knowledge of DFM. The results infer that a majority think that Loughborough students are on par or have a better understanding of DFM than other universities. Only 6.7% believed that an alternative degree course produced students with better understanding of DFM.

Additional Comments

Finally, the last question allowed the companies to express any other information relating to the students' knowledge of DFM. 10 participants answered this optional question. Of these ten, seven of the companies expressed that although the designers started with a basic knowledge, in some cases suggesting it should be better, by the end of the placement the designers showed vast improvements. Another point that was raised multiple times was a distinction from PD and ID students. It was highlighted that PD students were more capable at manufacturing related tasks and, one response expressed that 'both pathways should have the same knowledge of DFM'.

Student-Company Comparisons

The following data sets directly compared the results from the student and company questionnaire to look for any similar or contrasting opinions. Figure 8 shows a very strong correlation between the students' and companies' opinions of the four most important skills of the designer. Both parties show a strong bias towards CAD, followed by DFM. Sketching and rendering was chosen as the third most important skill. Sustainable design, electronics, mechanics and marketing were not considered within the most important skills.

However, there was more disparity between the areas in which LDS teaching needs to be improved upon. The graph, figure 9, shows that 61% of companies prioritised CAD as being an area which needed improvement, whereas only 37% of students felt that CAD teaching required this development. Similarly, there was further disparity between the companies' and students' opinions of marketing and electronics. Conversely, DFM was not one of the subject areas where the students and companies differed in opinion, being selected as the most popular answer for both.

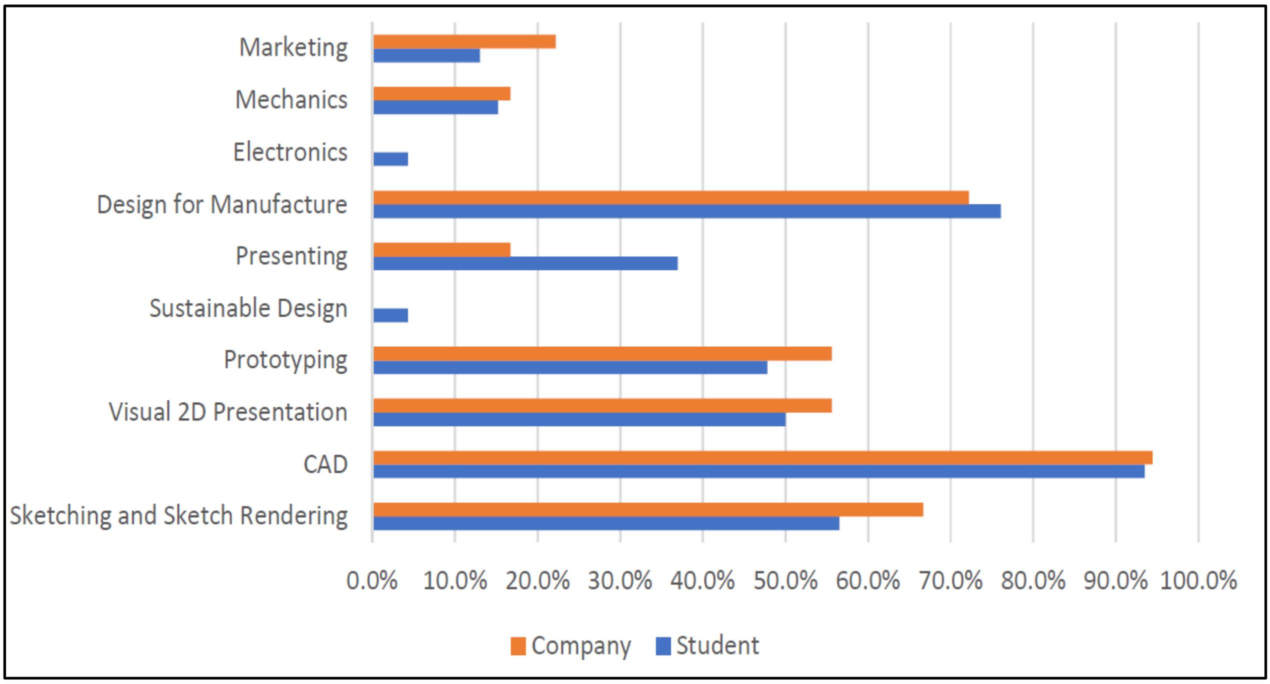

Figure 8: Comparing companies' and students' opinions on the most important skills of the designer

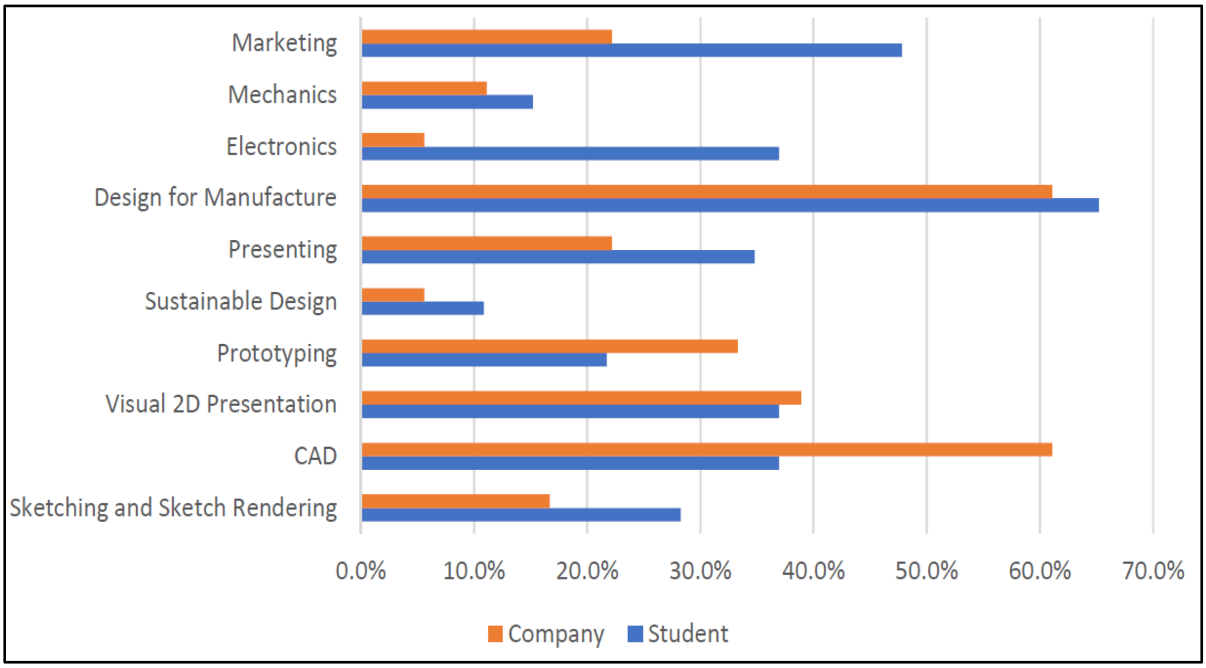

Figure 9: Comparing companies' and students' opinions towards areas of design education that need improving

When studying whether students had sufficient knowledge to carry out their role, the results between the two surveys were similar. On a scale of '1' to '5', the most popular answer from both sets was '3'. Meaning they neither agreed nor disagreed with the statement. Nevertheless, the second most frequent answer, for both parties, was that they agreed that the students had enough knowledge to fulfil their role.

Discussion

Within this research two surveys were conducted to assess the quality of DFM teaching within Loughborough Design School. The first survey was directed at both current and graduate students from LDS. The second survey was aimed at companies who had previously employed Loughborough students for either placement or graduate roles within their design teams. Initially, the surveys looked at which elements of design were most relevant to professional practice and which subject areas particularly required improvement in terms of teaching. Next, both the surveys targeted the general understanding of DFM. Lastly, both parties were asked to discuss further details and opinions about how DFM should be improved. This section will now go on to further analyse these results to determine whether the teaching of DFM at Loughborough Design School is meeting the requirements for students, allowing them to carry out their roles adequately within a professional design team.

Student Questionnaire

Within the student data sample, the number of students from the Industrial design course and product design course were almost even (47.8% ID and 52.2% PD), whereas there were a greater proportion of undergraduate responses (73.9%) compared to the 26.1% of graduate students. Of the complete student population, only 8.7% had no professional experience at all, meaning that a large majority of the respondents have been involved in both education and professional practice. This allowed them to provide comparisons between their learning and the application of DFM within industry.

The students then were asked to rate the four most relevant skills for professional design practice, before answering which area of their university teaching needed the most improvement. Interestingly, CAD (93.5%) was rated considerably more important than sketching and sketch rendering (56.5%), demonstrating how the designers have become increasingly reliant on digital techniques as suggested by Nichols (2013). DFM was the second most frequently selected option, 76.1%, signifying that students understand the importance that DFM has within professional practice.

When the students were asked to specify the subject areas that required the most improvement, DFM was selected most frequently (65.2%). When comparing this to the previous question, to identify the most important subject areas, one can see that DFM is both important and requires improvement. Therefore, it can be concluded that DFM is a key area of design in which the students believe that the education needs development.

A majority of design school students (60.9%) believe that the LDS has improved their knowledge of DFM to some extent. Out of a scale of one to five ('1' being strongly disagree and '5' being strongly agree) the mean result was '4'. However, when asking if this knowledge was enough for professional practice, the results are less positive, with a mean result of '3'. Comparing the mean results indicates that although the student's knowledge of DFM has improved, they also believe that their knowledge of DFM was not necessarily sufficient for professional practice. However, with a relatively small difference, caution must be applied to this conclusion.

Furthermore, comparing the results of PD and ID students, when asked whether they felt the teaching of DFM was sufficient for professional practice, there seemed to be a level of disparity. PD students felt their knowledge of DFM, on average, was more satisfactory than ID students. These results support Bingham et al.'s (2015) findings that the PD students are taught more in terms of engineering and therefore, it could be suggested that the ID course requires more improvement. Alternatively, it could be argued that industrial designer needs less knowledge of DFM for their role within industry. However, it is important to note that the research covered within this research does not go into detail about these specific differences between ID and PD and, therefore, further research would be needed to assess this difference.

Additionally, the participants were asked to differentiate between the taught DFM within university and the DFM applied within industry. The practical section of the DFM module, the injection moulding project, was frequently highlighted. Overall, the students felt this module was positive as an idea, echoing the results of Marshall and Page (2016). However, the extent of this success was limited due to the lack of real-world application. One graduate student stated that: 'the principles learnt for injection at university are wrong. It's teaches you exactly what you can't do in a mould tool.' A notion repeated by several participants.

Subsequently, the students were tested on their basic understanding of DFM. The results reflected positively on the teaching at Loughborough Design School, as all students grasped a basic understanding. Following this, they were asked to identify the stage at which DFM should initially be considered within the design process. This question was based on the theory outlined by Magrab (1997), that the most influential decisions on manufacturing costs are made at the concept stage. Therefore, DFM should be considered at the earliest point within the design process as costs of additional changes increases exponentially. The results showed that most participants chose the design development stage (second stage) as the preferred option (56.5%). However, when comparing undergraduates to graduates, it was apparent that graduate's results aligned themselves with the initial theory with 58.3% considering DFM within the concept stage (first stage). Similarly, when asked about the stage at which the largest manufacturing cost was determined, most undergraduates selected the design development stage again, whereas, most graduates selected the concept stage. This suggests that the taught DFM is not considering the implementation of costing and this is only realised when students have more industry experience.

Finally, the students were asked whether LDS needed to improve its teaching to prepare for professional practice and provide suggestions on specific areas of improvement. As before, the initial question asked for an answer on a scale of '1' to '5', providing a mean result of '3.6'. This suggests that slightly more students felt that the teaching needed improvement to better prepare for industry. Of those that felt improvements were needed, 75% proposed that DFM specifically needed improvement. Moreover, some felt that the heavy weighting towards visual techniques, comparatively to subjects like DFM, did not correlate within their proportional emphasis within professional practice.

Company Questionnaire

The company questionnaire targeted product design companies that employed Loughborough ID and PD students as either placement or graduate employees. This was a chance to understand if the companies thought students' knowledge of DFM was relevant and enough to participate in professional design practice. In the sample of companies, all agreed that taking on a placement or graduate from LDS has been a successful experience for the company. The unanimous result reflects positively on the overall teaching of LDS students.

To understand how much of an influence DFM had on this positive feedback, it was necessary to recognise how important DFM is within professional practice. Of the companies surveyed, 94.4% selected CAD as one of the top four most favoured skills from a design student. DFM was the second most popular answer (72.2%), whilst 66.7% selected sketching and sketch rendering. These results show a reliance on CAD, indicating professional design companies value CAD based skills more than traditional sketch based activities. These findings are in agreement with McCullagh (2010) who states that newly developing role of the designer needs less emphasis on traditional craft techniques. Furthermore, a high response rate for DFM, clearly demonstrates the importance of it within industry.

Additionally, the companies were asked to highlight subject areas that needed improvement. Both CAD and DFM stood out, with 61.1% of companies selecting these areas. On the other hand, sketching a sketch rendering received only 16.7% selection rate. These results echo earlier comments made by students suggesting that LDS puts too much emphasis on sketching techniques and more is needed in technical subject areas, such as DFM, for students to be able to better understand real-world design issues.

Next, the companies were asked about which stage during the design process they first considered DFM. 73% selected the initial concept stage as the right time to consider DFM, showing that the companies agreed with the initial theories outlined by Dewhurst & Boothroyd (2003). It can be assumed that the reason for this knowledge is due to their experience of cost implications when making changes later in the design process.

In addition to the previous question, it is known that the concept stage of new product development is a task most commonly completed by industrial/product designers (Ulrich & Eppinger, 2003). From this we can deduce that ID and PD students would make a substantial contribution to the DFM within professional practice. This theory is reinforced by the company survey, which found that 57.9% clarified 'in house industrial designers' made the biggest contribution to the DFM of a new product. From this we can conclude that the changing role of the designer requires knowledge of manufacturing and CAD, as well as more the traditional design techniques such as sketching and model making - once again echoing previous findings. These ideas are further backed up by 89.9% of the companies who disclosed that ID and PD students are 'always' or 'often' exposed to DFM when employed in a design based role.

To give further understanding of how successful the teaching of DFM is at LDS, the companies were asked to give their opinion on a scale of '1' to '5' ('1' meaning strongly disagree and '5' meaning strongly agree), if the students arrived with good knowledge of DFM when they started, and whether this knowledge was enough for their role within their company. This gave mean results of '3' and '3.3' respectively, suggesting that the companies thought that although the students' knowledge was not poor, neither was it excellent. Alternatively, this data could be interpreted as unknown, however, as previous results demonstrated, companies do believe an improvement in DFM is required.

Following this, companies were asked to state any differences they noticed between the LDS teaching of DFM and the necessary skills for DFM within professional practice. Comparable to the student responses, several companies expressed that the injection moulding project, run at LDS, did not prepare the students for mass manufacturing circumstances. They claimed that it should have: 'better links with real world situations' and students should have 'better understanding of budget restraints'. On the other hand, companies had the opinion that there would be an 'understandable lack of experience' which is best taught within industry. It is important to state that the companies used for this survey were those involved in new product development and, therefore, it would be wrong to assume that all students with placement experience would gain sufficient knowledge of DFM. Again, reiterating the need for LDS to teach DFM fully.

Moreover, companies did not think students from alternative universities had any better knowledge than those from LDS. In fact, 40% thought that students from other universities had noticeably worse knowledge, inferring that LDS's teaching of DFM is better than other courses. However, further investigation into how different design courses are run and how they teach DFM, would be needed to validate this point.

The final question gave the companies an opportunity to express any further information relating to the student's understanding of DFM. Overall, the answers concluded that although the LDS students started with a basic understanding of DFM, by the end of the placement, vast improvements were shown. From this, it could be suggested that the if all students were required to take part in professional practice, then the course's teaching of DFM would be less significant, as this would happen naturally within the student's experience in industry.

However, the majority of companies suggested that improvement of DFM teaching would be useful for the student to integrate better within the company. In addition, it cannot be guaranteed that all of the companies that employ LDS students would include DFM within their work.

Finally, an interesting point raised by more than one participant, was the distinction between ID and PD students. This suggests that PD students were more capable of completing manufacturing related tasks than ID students. One participant suggested that the same education of DFM should be apparent within both ID and PD courses. This clarifies Bingham et al.'s (2015) findings that the PD students at LDS are taught more engineering based subjects compared to the ID course. Furthermore, although the courses are taught differently, the professional roles that the students are employed within are similar. Hence, it proves that this needs to be adjusted accordingly and begs the question of whether the ID course is outdated due to the new role of the designer. More research would be needed to establish whether this is the case.

Direct Comparisons between Students and Companies

Following a comprehensive review of the student and company questionnaires individually, some of the results have been directly compared in order to conclude to what extent DFM teaching at LDS is successful at preparing students for professional practice. Initially, the first results to be compared, were the questions surrounding the key areas deemed to be most important for the role of the designer. There was a very strong correlation between results from both parties, with mutual agreement that the top four skills, in order, were: CAD, DFM, Sketching and Sketch rendering, and Visual 2D presentation. These results conclude that CAD and DFM are understood to be the most important for professional practice.

Both surveys asked the respective participants to identify the subject areas which needed the most improvement. There was more disparity between the two results when selecting subject areas such as CAD and marketing. Conversely, both parties selected DFM as the area which needed the most improvement. From this unanimous decision, it can be concluded that the teaching of DFM indisputably needs refinement.

Additionally, it was found that that the majority of companies consider DFM at the concept stage, whereas the majority of students thought that DFM shouldn't be considered until the design development stage. This difference highlights that students lack a more thorough understanding of DFM and its benefits, which are applied throughout professional practice. This is most likely because costing is not a key part of the curriculum and, therefore, possibly indicates a way in which LDS could improve their teaching of DFM. Furthermore, this result also suggests that the teaching of DFM is rarely approached early enough with the design process, which supports one student's feedback that stated: 'DFM is considered immediately in industry, whereas in the design school it appears to be an afterthought'.

Finally, the opinions of both students and companies were compared, in terms of whether they thought that LDS students had enough knowledge of DFM to carry out their profession role sufficiently. Both students and companies felt that knowledge was slightly better than average with a combined mean result of '3.6'. However, in comparison to the overall positive success of employing Loughborough students, this result is relatively poor. Therefore, combining this feedback with the newly understood importance of DFM, LDS needs to improve this area of teaching.

Conclusion

Within this research both primary and secondary research was undertaken to assess the importance of Design for Manufacture (DFM) within professional practice, comparing how it is taught within education to prepare students for industry. The research provided several interesting findings. Firstly, it was discovered that both students and companies agreed that DFM was regarded as a key skill utilised within professional practice. This was also found within the literature review, as multiple sources highlighted the benefits of DFM in relation to the role of the professional designer.

Next, it was posited by a number of sources within the literature review, that the role of the designer has evolved, changing from traditional craft based skills to more engineering based skills. These new DFM skills were identified by all the surveyed companies, stating that LDS students were 'always' or 'often' exposed to DFM whilst employed. Furthermore, a majority of companies claimed that 'in house industrial designers' made the largest contribution to DFM, further enhancing the importance of DFM to the newly defined role of the designer.

Having specified the new, evolving role of the designer, in which the prominence of DFM is seen as more important than craft skills, the weighting of these areas taught at LDS did not correspond to the level of importance within industry. It was highlighted that LDS students had an inadequate understanding of when DFM should be applied within the design process. This timing was found to be crucial within industry in order to remain cost effective.

Additionally, the difference between ID and PD students was highlighted by both the primary and secondary research. The results showed that ID students were taught less about engineering techniques, resulting a lesser knowledge of DFM. It can be concluded that the ID course needs the most improvement of DFM teaching, in order to better prepare students for industry. However, further studies would be needed to fully understand the differentiation between these two disciplines.

Finally, it was ultimately decided that it was successful for companies to employ LDS students. However, this positivity wasn't reflected in the companies' opinions about the student's capability and understanding of DFM, yet again reiterating the need for improvement within this area. To conclude, design for manufacture is understood to be a vital for the newly defined role of the designer. Although the teaching of DFM at Loughborough Design School supplied the students with some knowledge, it does not entirely meet the requirements for professional design practice.

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