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PROJECT BASED LEARNING AND REFLECTION IN A MANUFACTURING ENVIRONMENT

Marijn Zwier, Eric Lutters, Lisa Gommer

Department of Design, Production and Management, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands

ABSTRACT

In engineering education, many initiatives aim to close the gap between theoretical knowledge and practical/industrial application. The course depicted here focuses on the injection moulding of an elementary plastic product, and aims to address the full development cycle, ranging from product idea, via 3D modelling, simulation of injection moulding processes, mould design, process planning and milling of the mould, to the actual injection moulding. In this, continuously reflecting on the initial ideas, new acquired knowledge and information, provided limitations and intermediate steps by the students themselves drive the iterations in the overall cycle. The course has a specific focus on acquiring needed information, the students are assumed not to just study and apply existing (design) rules for injection moulding; they rather are challenged to deduce the design & manufacturing rules that bear relevance and give guidance for their development cycle. In this, basic knowledge is provided to the learners in short lectures, videos, and tutorials, albeit they are simultaneously challenged to obtain, digest, and apply additional knowledge on the various topics if and when needed. Over the past five years, over 100 injection moulds and products were created, for an equal number of student groups. This demonstrates that second year students (in this case Industrial Design Engineering students) can successfully associate with such a complex development process. Evaluation among the students indicates a high level of understanding and motivation linked to the creation of their own actual product. By means of the approach chosen, the course not only aligns the intended learning outcomes, the learning activities, and assessment tasks. It simultaneously triggers the learners to build expertise and experience at different levels of aggregation, in a self-propelled manner, with full ownership of the project.

KEYWORDS

Project based learning, Plastic injection moulding, Development trajectory, Standards: 5-8

INTRODUCTION

The educational programmes in engineering at the University of Twente have a long tradition in applying project-led education as a means to inspire and challenge students and to allow them to study and experience the relation between theoretical knowledge and (industrial) practice (Dankers et al., 2013). Especially in the BSc. programmes, the curriculum is characterised by the amalgamation of projects and theoretical courses; in every educational module of ten weeks, students enrol in a project that thematically coheres with adjacent courses. Dependent on the specific project and level of studies, typical group sizes range from 4 to over 15 students per group, where the efforts involved in the project represent 20-50% of the overall study load. In the projects, students inherently need to take ownership of their own projects, take the responsibility for the outcome, but also for the process that led to that outcome. By steadily reflecting on the learnings and progress, student motivation to internalise knowledge increases, as is their inclination to purposefully apply that knowledge. This also makes assessing education more transparent and purposeful (Biggs & Tang, 2011), as students themselves are involved in correlating activities to goals and deliverables. In the curricula, different projects immerse students in different perspectives, with different starting points, scopes and development approaches. With that, students are inherently accustomed to dealing with different situations and the uncertainty involved. This challenges them to not 'just' straightforwardly try to solve the problem at hand, but to also look at the consequences of solution for other perspectives, to establish co-operation over different disciplines but also to question or reformulate the problem statement (Fresemann et al., 2018; Luttikhuis et al., 2014; Berglund et al. 2007). This allows students to emphasise their own profile within the programme, as they can focus on different roles in subsequent projects.

Within the context of project-led education, the educational programme Industrial Design Engineering continually strives to offer original educational approaches, thus applying the originative character of the programme – not only as the content is concerned, but also addressing novel educational approaches, software, technology and relations with industrial reality. This publication depicts a course in the second year of the programme that allows students to transcend the scope of an individual design step or production process.

COURSE SETUP

In the course, students peruse the development process of an elementary plastic product. They do this in small groups, of four to six students each, in a ten-week project that covers around 20% of the nominal study load. The development of the elementary plastic product starts with a straightforward challenge that is assigned all (around 30) groups before any knowledge transfer takes place: "design a plastic product that can be produced using a single-sided mould". The students are given complete freedom in their design decisions in terms of for example geometry. However, the students quickly understand that this uncomplicated assignment implicitly incorporates a wide range of limitations and perils related to individual process steps, manufacturability, feasibility and quality of their design (Andersen et al., 2021), but also to managing the entire development cycle. Moreover, given the number of students involved, a number of more pragmatic restrictions are imposed from the perspective of course management. In the first seven weeks of the module, students address the full development cycle, ranging from product idea, via 3D modelling, simulation of injection moulding processes, mould design, process planning and CAM (see figure 1), using industrial software.

The remaining three weeks are used for production of the mould (two weeks) and the actual injection moulding (one week). With around 30 moulds to be manufactured in a time span of two weeks, and the capacity of the workshops at the university, the lead-time for all the moulds is a main bottleneck in organising the course project. This entails that the students are provided with several technical design limitations – simply to enable mould production for all groups. At the same time, those limitations immediately confront students with the fact that downstream processes do influence early design decisions. On the one hand, the limitations help groups to make the assignment more manageable. On the other hand, groups that reflect on the cause of the limitations and can generalise that reflection can benefit significantly in addressing other phases in the course. Another origin of technical design limitations is the fact that the design must be injection moulded on the one available machine. Hence, together with the assignment, the students receive information on and specifications of the injection moulding machine setup. The course setup corresponds well to all four sections of the CDIO Syllabus 2.0 (Crawley et al. 2011).

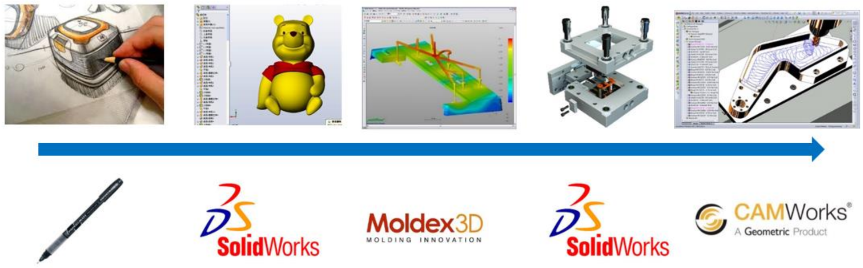


Figure 1. Schematic representation of the course phases/topics and their dependencies

Injection moulding machine setup

The practical orientation of the course requires a series of production machines, tools and standard parts in order to successfully injection mould the products designed by the student groups, in a setting that can be characterised as a learning factory (Abele et al., 2017). For injection moulding, a BOY 22E injection moulding machine is used. This is an industry standard machine suitable for small products with a maximum shot volume of 47 grams, a maximum injection pressure of approximately 1000 bars and a clamping force of 22 tons. The students need to interpret the implications of these machine characteristics for their own design, especially during the simulations of the injection moulding process.

For reasons of handling and flexibility, the injection moulding machine has a so-called unit die holder. The unit die holder developed for this course contains e.g., cooling channels, the ejector plate, sprue bushing and numerous guide pins and bushes (see figure 2). It acts as a base for the mould inserts created by the students, making the inserts simpler hence allowing for faster milling. The mould insert, from here on referred to as mould, is an aluminium block measuring 160x140x25 mm. Whereas moulds for mass production are made of hardened steel for durability, this project applies aluminium to significantly reduce milling times. For the milling of the moulds two Datron M8 Cubes and a DMU CNC milling machines are available.

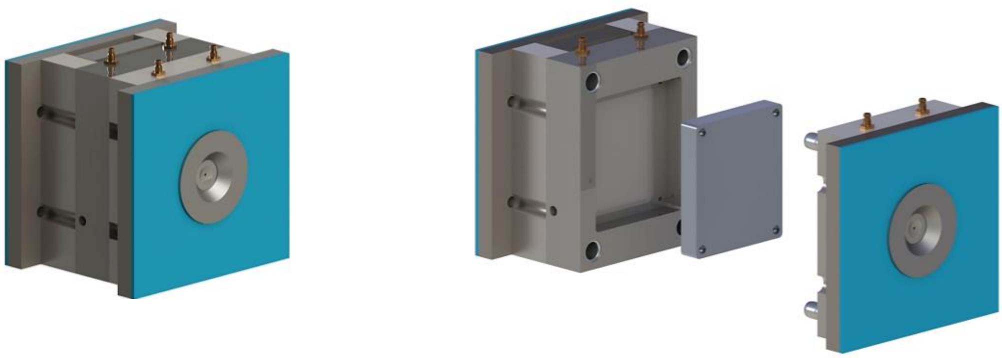


Figure 2. unit die holder with mould insert and second mould half.

Limitations

At the start of the course, students are exposed to a scenario that introduces them to the actual production of the moulds and their actual plastic products. At the same time, this scenario is the basis for the students to foresee and understand technical limitations that will play a role in the decision making in their project. In short, the scenario shows the groups that, to contain the complexity of the design assignment and to allow for the production of all moulds, groups are limited to a single mould side, the cavity. The other mould half, called the core, is a simple flat side with the plastic injection point located at the centre. This centre point, the so-called runner-start point makes the connection between the sprue and the runners in the students' moulds. The dimensions and shape of this start-point are stipulated and provided as a 3D CAD model. The designed moulds are made by milling, in which a specific set of milling tools is available, a.o. flat end, ball nose and tapered end mills. The minimal tool diameter and allowable cutting depth can significantly impact the final product geometry and the surface quality. For example, the minimum available tool diameter is 1 mm, resulting in minimum applicable corner radius of 0.5 mm.

Once the mould is mounted on the injection moulding machine, the machine parameters in production should be underpinned by decisions in design and simulation activities. Adding to that, after opening the mould halves, the product can be ejected automatically by the ejector-pins. The location of the ejector pins is limited due to the construction of the unit die holder. The centre of the mould allows for freely positioning ejector pins in a region measuring 95x75 mm, which is considerably smaller than the region available in the mould. Also, the ejector pins have a fixed diameter of 3 mm and standardised lengths. The length of the pins is linked to the depth of the cavity measured from the mould parting surface. Pins for depths of 1, 1.5, 2, 2.5, 3, 4 and 5 mm are available.

Presenting the student groups with a scenario like this allows student groups to contextualise their design decisions, to look beyond the 'next' decision, but foremost to challenge them to structure their own project and to take ownership thereof. Together with the straightforward assignment, this contextualisation presents the student groups with an actual and concrete challenge, in which they themselves have to uncover, retrieve and generate the information that will allow them to reach the decisions they consider to be contributive to their project. Over the years, this approach has been the basis to really immerse the students in challenge-based learning – especially as the groups can actually produce their designs and as the groups tend to start a competition amongst themselves.

COURSE PLANNING

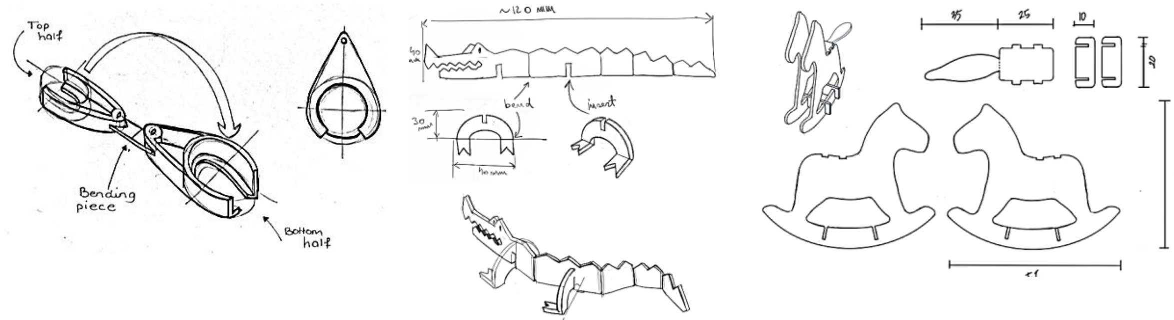
Week 1 and 2

The first week of the course is used to explain the course setup (as shown in figure 1) with all the different phases and software programs the groups will be using in the subsequent seven weeks. The assignment is introduced, together with the scenario that outlines the technical data of the machine tools, tools and processes involved and the resulting (im)possibilities and limitations. Obviously (and intentionally), this overwhelms the students, because not all information seems immediately relevant for the first design phase. Consequently, the students need to analyse and internalise the information and underlying knowledge provided to single out which information is relevant when and what information may be incomplete, uncertain or lacking. For example, providing the clamping force of the injection moulding machine might seem to only bear relevance for the final stage of setting up the injection moulding machine. However, together with the injection pressure, the clamping force is inextricably linked to the maximum frontal surface area of the mould cavity. A product designed with a large frontal surface area might exceed the maximum clamping force of the machine, resulting in failure during production. Therefore, students have to deduce that clamping force and thus surface area are relevant already during the first design phase. Another example of information that seems only relevant for the final injection moulding process is the length of the ejector pins. If during the design phase this pin length is disregarded, the product thickness will not match the available resources – in this case leading to clear imprints of the pins and thus surface imperfections being visible in every product produced.

To provide guidance to the students in the process, short lectures introduce topics related to the design and manufacturing of plastic projects and create awareness of the interdependencies of the topics involved. Lectures include general design guidelines, mould design and layout, and an introduction into melt flow characteristics in cavities. Again, students are assumed not to just study and apply existing rules for injection moulding; they rather are challenged to deduce the design and manufacturing rules that bear relevance for their own product and development cycle. As the design freedom in the assignment yields a huge variety of resulting designs, no lecture provides knowledge that is fully and unequivocally applicable for any individual design. Again, this stresses the need for students to revise all input to render it meaningful for their design. To aid students, throughout the entire development process, teaching assistants are available for consultation. The combination of design freedom and working in groups creates a de-centralised teaching setting, where groups can get feedback and guidance, linked to their design, but based on generic theoretical knowledge.

To spur decision making, groups have 1.5 weeks before they have to hand in the final product idea containing sketches (see figure 3), explanations, and substantiations of their design. Each group receives feedback, based on the guidelines used, envisaged manufacturability of the mould and producibility of the product. Based on the feedback, students can iterate on their design, their assumptions and their design decisions before starting the first simulations.

From figure 3 it is clear that the given limitations, especially the use of a single-sided mould, results in 2.5D products. Most final products are built by combining different 2D parts into something of a 3D structure using slots or hinge mechanisms. Such mechanisms entice students to learn about e.g., material behaviour and tolerancing/accuracy while also introducing additional interrelations between the design and downstream processes.

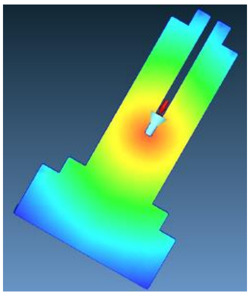


a) Coin holder b) Crocodile c) Rocking horse

Figure 3. Examples of product idea sketches

Week 3, 4 and 5

After finalising the product concept, 3D SolidWorks models are created by the students to prepare for injection moulding simulations. For the simulations the software package of Moldex3D is used. This software program is one of the two main simulations packages used in the injection moulding industry and thus a great way for students to get acquainted with such specific software. In this phase of the course, the students will establish the first feedback on their insights on the producibility of the product. The first step in the simulation is the determination of the gate location (the melt inlet for the product cavity). The software has a built-in tool to determine the optimal location, but students still need to correctly setup this optimisation and reflect on the results. For example, the gate cannot be positioned on surfaces that interfere with the functionality of the product. Figure 4a shows the optimal gate location according to the software, but this location coincides with a slot for combining parts. The students could overrule the software and decided to reposition the gate to the best possible position close to the optimal location without interfering with the functionality (see figure 4b).


a) Gate location optimisation by software

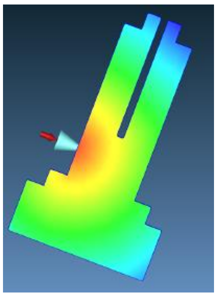
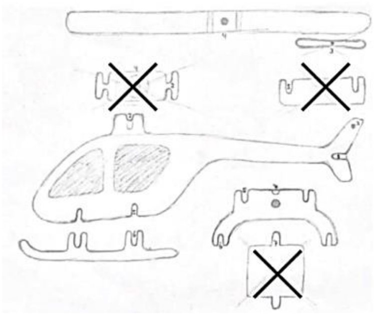

b) Adapted gate location by students

Figure 4. Example of adaptation of gate location

Before starting a complete filling analysis, the students need to determine the position of all parts in their mould. This first positioning is done based on the information provided during the lectures on mould layout in combination with the area that is available for ejector pins. Each year, multiple groups have to iterate on their design or have to reconsider earlier design decisions (for example to simplify their design or remove small parts, see figure 5a) because of the lack of ejector pin options. Figure 5b shows a tight arrangement of parts within the mould in such a way that every part has ejector pins at proper locations.


a) Reducing parts because of ejector pins

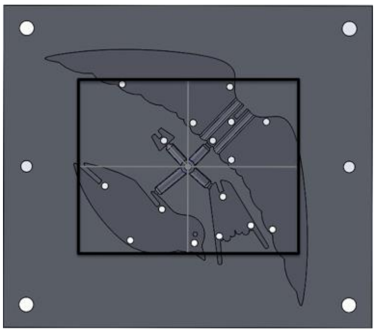
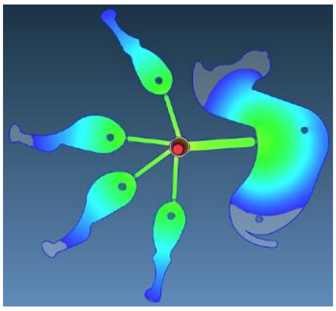

b) Part arrangement to pin region

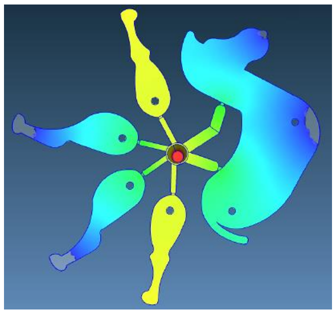
Figure 5. Ejector pin positioning

The next step is to simulate if the part cavities can be filled with plastic by setting up a flow simulation. This is where the product really comes to life for the first time and students start to realise that if these simulations are not successful, the actual injection moulding process would fail accordingly. This clearly and visibly motivates groups to critically reflect on all simulations and simulation results – also urging them to iterating on their own design. In all simulations students asses the values, impact and mutual dependencies of over 20 different process parameters and characteristics, including e.g. the location of airtraps and weldlines, temperatures, pressures, stresses, clamping force, shrinkage and warpage. To help the students with the interpretation of the results, short videos about individual parameters and characteristics are made available.

An important aspect in injection moulding is the simultaneous filling of all cavities in a single mould. Any mismatch in filling time will result in pressure differences that can lead to differences in shrinkage and other deformations. Especially student groups that designed 3D products build up by 2D shapes, as seen in figure 3, will have to monitor this closely. For example, the figure 6a shows the melt flow for a 3D Zebra where two of the legs are filled at 81% of the total filling time. This is well below the industry standard of 90%. After several iterations, the group concluded that the body needed two gates instead of one. Where this causes the two legs to now be filled at around 91.5% of the total filling time (figure 6b), this solution will inherently introduce a weld line, forcing the students to assess and prioritise the (dis)advantages of either approach.



a) Flow simulation, two legs filled at 81%



b) Flow simulation, two legs filled at 91,5%

Figure 6. Example of melt flow optimization

Week 6 and 7

After finalising the simulations, the last two weeks of the 7-week development cycle are spend on creating the CAM files for the production, see figure 7a. The first step for the students is to create the negative imprint of their product resulting in the mould block with product cavities. This forms the basis for the creation of the process plans, using the software package CAMWorks. The software contains all tools that are available for milling the product cavities, together with the proper machine settings. To help the students, a tutorial and videos describing all steps, for a similar product, are made available.

Creating the milling toolpath often reveals design errors that have gone unnoticed before. As mentioned in the section about limitations, the smallest available mill has a diameter of 1 mm. This means that no toolpath can be created for cavity parts that are less than 1 mm in width. Every year, multiple groups are confronted with the significant consequences of this constraint. For example, if the gate is made too small and must be enlarged, this invalidates the previously made simulations, gate size has a significant influence on pressure, melt flow and more. Groups are forced to redo parts of the simulation to verify again that the product can be produced. Examples like this clearly show the complex and iterative development process the students are faced with. Another example with milder consequences is the impossibility to create sharp internal corners with rounded tools. Every internal corner will have a minimal radius equal to the radius of the used tool. When creating the toolpath this often leads to geometry left un-milled at these locations, slightly alternating the final product geometry. These changes do not have a large impact on the simulations but will change the appearance of the product and will also influence the exact amount of material required in injection moulding. To avoid this, students are encouraged to think about the negative or imprint of their product during the first stages of the design process.

a) CAM file containing toolpaths b) CNC milling of the moulds

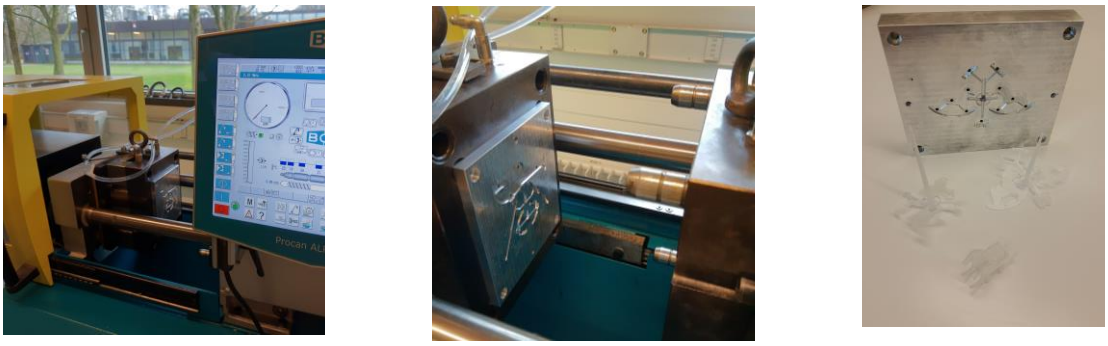
Figure 7. Mould production from CAM file to CNC milling

Week 8 and 9

In these weeks the production of the mould takes place (see figure 7b); for safety reasons the CNC-machines are operated by members of staff. Moreover, all CAMWorks files, containing the CNC code with all necessary milling steps and setups are checked extensively. This is a very labour-intensive task for the lecturer. However, this check not only ensures that all steps and setups are correct to prevent failures during production, but the files also provide valuable insights in the decisions, assumptions and quality assessments by the students in the group. Consequently, these files do also play a role during grading. When files contain too many or significant errors, groups are notified, provided with feedback, and asked to provide improved versions. In the same two weeks the students have time to finish the project documentation containing design information about their product, the underpinning and results of the simulations performed and the analyses, evaluations of and reflections on the simulation results and on the development process that led to those results.

Week 10

The final week of the module is used to produce the products. In a session of approximately 45 minutes per group, students will mount their mould on the injection moulding machine (see figure 8a) and propose machine settings based on the simulation outcomes. If those setting are considered viable and safe, they will be used in the first injection moulding run. Together with the lecturer the group can then advance in obtaining more appropriate/optimal process parameters, based on the available simulations and based on observations and measurement on the actual injection moulding machine. In general, this optimisation process (see figure 8b) takes 20 minutes. The remaining time is spent on fully automated production, resulting in a product every 30 to 45 seconds, depending on the cooling characteristics of the design.



a) Mould mounted into the injection moulding machine b) Final product

Figure 8. Injection moulding in the final week

COURSE EVALUATION

By now, the course yielded over 100 moulds for injection moulding, for as many student groups in the past five years. In these years, four groups failed to deliver a CNC worthy mould and around 25% of the groups had to do some supplementary work before mould production could start. The final injection moulding of the products also exposed design flaws. Common design flaws are i.a. too few ejection pins, missing of draft angles, too small gates. Overall, 10-15% (per year) of the products are stuck in the mould due to this, ranging from the need of manual removal to complete fixation of the product in the mould. Other mistakes common in industry like short shots, excesses clamping force or acceding any machine limits never happened, proving that the simulations are properly performed by the students. Also, over the years the complexity of the products increased, as students have explored (and tried to push) the boundaries of what is possible within the technical limitations. Complex snap fits, hinge mechanism and metal inserts with over-moulding have successfully been produced. This demonstrates that second year students (in this case Industrial Design Engineering students) can successfully associate with such a complex development process. The increased complexity also means that students learned from and built on the work of previous generations.

The successful implementation is underpinned by figure 9, showing the grade distribution of the final course grade per individual student over the past five years. Students are graded on the CAM file, project documentation and final product. The CAM file and project documentation are graded by criterion referenced grading using a checklist/scorecard and rubric, respectively. The final products are norm referenced graded between all groups.

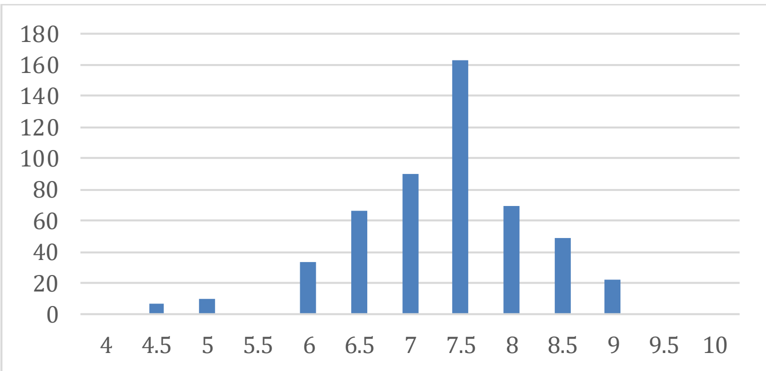


Figure 9. Grade distribution over the period from 2017 till 2022

Evaluations among students, performed every year after the course has finished also show the successful implementation of the injection moulding development process in education. The sessions are attended by approximately one third till halve of the students enrolled. Remarks that were mentioned several times during these sessions over the years include i.a.

- “It was nice that we did design our own product and we saw our own product being injection moulded. This was really motivating to work on the assignment.” Mentioned over 40 times in the last three years of course evaluation.
- “Interesting and fun course, learned a lot by completing the entire development process.”
- “The course taught students quite a lot and was relevant to their growth as industrial design engineers.” Mentioned over 20 times in the last three years of course evaluation.
- “It was a good way to learn about injection moulding, not only using theory, but also putting it to practice.”

Other feedback includes positive remarks on the multi-disciplinarity of the course, the hands-on approach, the opportunity to use ‘industrial’ software and machines and the ability to consult with the lecturer on all topics involved. Besides the predominantly positive feedbacks some students indicate that they would like to see a subsequent course that would allow them to work on a ‘real’ industrial product. Moreover, the student group size is and probably will be a point of criticism. Most students indicated that a group size of four to six students is too large for this course. However, from the perspective of course management, smaller groups, and thus producing more moulds, is simply not attainable, also because this would significantly impact the time for per-group feedback and pre-production checks. At the same time, the teaching staff is convinced that remarks on group size more often than not are actually reflections on team-work in role distribution in the group; where this is not an explicit learning goal in this course, the students clearly engage in thinking about their own and each other’s roles, interests, work-load, and responsibilities in the project. All in all, the evaluations performed during the five years of teaching this course, endorses the impact of the course and the effects of challenge-based learning at project level in manufacturing environments.

CONCLUSION

The developed course has proven that second year bachelor students can successfully, in small groups, go through the complex development process of creating an injection moulded product in a timeframe of 10 weeks. Simultaneously, the course is manageable for the staff, by tailoring the restrictions conveyed to the students carefully against the available capacity of staff and equipment. Also, active teaching efforts are gradually supported by providing access to theory, knowledge and best practices by means of short lectures, videos, tutorials and by making previous results of student groups available for scrutiny and as inspiration. The project-based approach challenges students to take ownership of and responsibility for their own injection moulded product and development trajectory. Groups continuously reflect on the evolving ideas and progress, while acquiring knowledge and dealing with restrictions. Such acquired knowledge drives the iterations in the development cycle, inheriting from industrial development trajectories. Because of the synergy between theoretical knowledge and practical/industrial application, the course allows students to see the full development cycle of injection moulding from multiple perspectives. Course evaluations are positive and indicate high levels of understanding and motivation linked to the creation of an actual product. Other feedback highlights multi-disciplinarity, the hands-on approach, the opportunity to use ‘industrial’ software/machines and the ability to consult with the lecturer on all topics involved. For subsequent versions of this course, focus will be on the way in which a structured information backbone (as an evolvement of the videos, tutorials etc.) can provide students with a contextualized, semi-industrial working environment. Also, an additional focus will be on design rationale and the deduction of design rules.

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BIOGRAPHICAL INFORMATION

Marijn Zwier: is a teacher at the Department of Design, Production and Management at the University of Twente. He teaches courses for bachelor students in Industrial Design Engineering and Mechanical Engineering. His interests include production technologies, injection moulding and product design.

Eric Lutters: is an Associate Professor at the Department of Design, Production and Management at the University of Twente. His research focuses on design and development trajectories – in education, research and industry.

Lisa Gommer: is programme director of the programmes for Mechanical Engineering and for Sustainable Energy Technology at the University of Twente. She has a background in educational sciences and has previously worked as an educational consultant.

Corresponding author

Marijn Zwier
University of Twente
Dept. of Design Production & Management
PO Box 217, 7500 AE Enschede
The Netherlands
m.p.zwier@utwente.nl