INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 05 MELBOURNE, AUGUST 15-18, 2005

IDENTIFYING AND ENHANCING CONCEPTUAL DESIGN CAPABILITIES

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Abstract

Significant research has been conducted into the design process associated with professional design engineers (those with university level qualifications), for example, [1][2]. An ongoing, collaborative research program has been initiated that seeks to identify, and hopefully enhance, the design capabilities of pre-university workers (those without university qualifications) whose roles are not traditionally associated with the design process, especially those phases associated with creativity and innovation.

The overall program seeks to facilitate improvements to existing injection moulding die design practices. The paper reports on work completed on novel methods to promote effective knowledge transfer to motivated pre-university workers and practicing designers.

This paper reports on our evaluation of the proposition that pre-university factory workers will gain a better understanding of design features and design attributes of a complex mechanical system through the use of three-dimensional rather than two-dimensional representations.

Keywords: *Design for manufacture, Design education, Empirical research through comparative studies*

1. Introduction

A need has been identified for the development of educational methods that can assist the knowledge transfer of design methodologies and advanced technologies to motivated pre-university workers [3, 4, 5]. The researchers have focused on the polymer industry sector and, more specifically, the injection mould design, manufacture and production cycle.

The research program seeks to:

- Review current practice to understand where improvements can be made.
- Survey the polymer industry sector to discover the prioritised requirements from a practical program of staged improvement within the sector [6].
- Provide suitable mechanical and manufacturing design tools to pre-university workers within the plastics technology sector – the focus of this paper [7, 8].
- Develop conceptual models associated with the relevant system functions that are appropriate to allow understanding by workers without the demonstrated mathematical and system modeling experience of tertiary graduates.

- Promote design innovation through an ongoing challenge of existing precedents. This will involve evaluation methods applying concepts such as efficiency (e.g. cost-benefit analysis) and risk assessment.
- It is hoped that these innovations will facilitate the capacity in pre-university workers to make informed and reasoned creative design contributions.

2. Methodology

A series of tools has been developed for this educational research program:

- Teaching materials that expose the worker to concepts associated with mould die design using traditional, paper based, practices including text, engineering drawings, diagrams and photographs (two-dimensional, 2D approach).
- A novel three-dimensional (3D) artefact (shown, in part, in figure 1) that highlights a large number of important die attributes. The artefact was developed as a result of an extensive investigation into die performance (moulding processes and associated defects). This artefact forms the basis of the 3D approach.
- A series of evaluation tests to assess knowledge and information retention of specific die design and performance attributes. Each test requires no more than five minutes to complete.

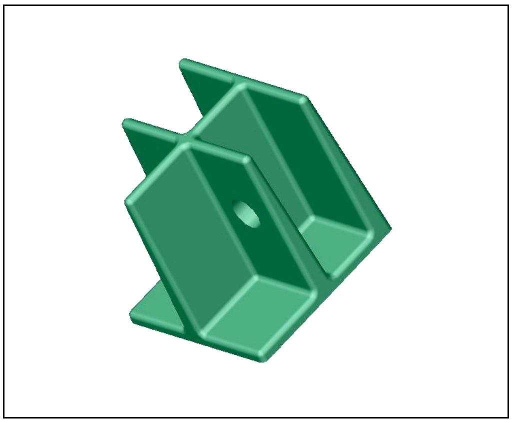

Figure 1. Image of the 3D moulding artefact to be used in the full study of this research programme. It contains a large number of moulding features, both advantageous and problematic.

Workers were introduced to a trial knowledge transfer course in the following manner:

1. They undertook a pre-education test to assess prior knowledge of the specific design attribute to be addressed;
2. The workers were split into two streams (group-1 and group-2);
3. The training courses were completed using the 2D approach for group-1 and the 3D approach for group-2;
4. Both groups completed a second, common, test about the same design attributes;
5. After at least two weeks, a third test was to be undertaken to compare knowledge retention of workers in each group (this work has not yet been completed);

6. If differences existed between the two groups, the better design attribute course would undertaken by the group with the lower achievement level (to preserve equity).
7. A fourth and final test of retention would be administered if training (6) was required.

3. Spatial skills measurement

Common methods used for on-the-job training employ illustrations and paper-based representations of equipment and machinery. However, the authors were unable to locate any data or research outcomes measuring spatial skills that has targeted subjects with a non-tertiary educational background, in order to justify the efficiency of such training method. The only measurements available are based on research conducted on university students or whole populations.

A standard test was given to subjects to evaluate their spatial skills. The subjects' visualization skills, measured with the MMCT (Modified Mental Cutting Test), has been used as the main criteria for dividing the sample into two groups. How spatial skill affects learning abilities, and which method (2D or 3D training) can prove to facilitate learning, have been investigated in this research.

3.1 Mental Cutting test

The MMCT consists of 25 questions. The subjects are required to determine the correct cross sectional view, using the associated pictorial view of an object being cut by a cutting plane. A sample test problem is shown in Figure 2. The time limit for the entire test of 25 questions is 20 minutes.

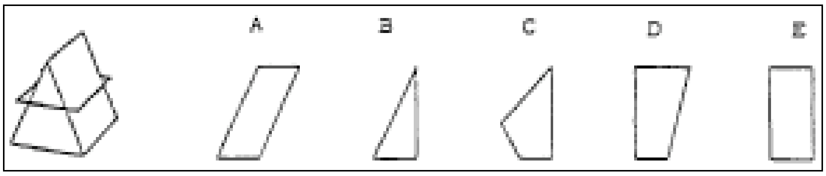

Figure 2. A sample MMCT question

3.2 Subjects

This section reports on the pilot study completed on a small population of factory workers and office administration staff. The format presented will be that used for more substantial studies as candidates become available within the overall research and training program.

The population sample under investigation consists of six injection machine operators from a plastics company and four administration staff of a manufacturing training organization. The plastics company supplies decorative and protective automotive components to all four main Australian car manufacturers.

The machine operators are in charge of injection moulding machines, visual quality inspection of produced products, and packing the manufactured products. They have had no formal training on the machinery and processes, and very limited knowledge of the plastics material. Administration staff have regular interactions with the shop-floor workers and have had several tours of manufacturing companies. They had observed the process and machinery but have either zero or limited knowledge of plastics processes and tooling.

Subjects in the training sample are 70% female, with a female-average age of 36 years and a male-average age of 43 years. The overall population sample has a wide age range: 22 to 60 years, with the average of 38.3 years. The educational background of the subjects is summarised in figure 3.

None of the subjects had completed a similar spatial skills measurement test before. They needed significant time to read and understand the test instructions before starting the test.

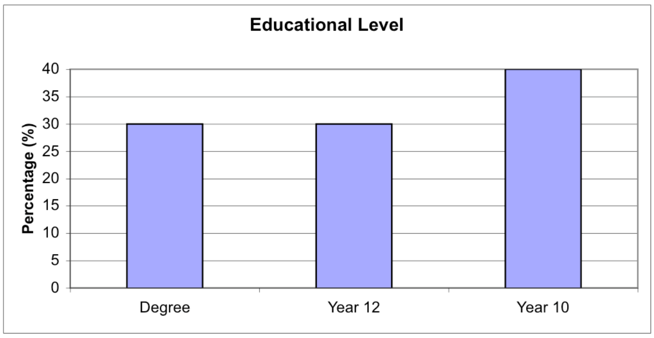

Figure 3. Educational background of subjects (highest level achieved)
Year 12 is the final year of secondary study in Australia prior to University.

3.3 MMCT test results

The administrative staff scores were 14 (male, degree), 11 (female, degree), 10 (female, year 12) and 1 (female, degree) out of a maximum of 25.

The machine operators scored 8 (female, year 10), 3 (three operators scored 3: two female and one male, all year 10), 2 (female, year 12) and 1 (female, year 12).

The mean score for the MMCT was 5.6, with a standard deviation of 4.47, i.e. (mean = 5.6; SD = 4.47). Administration staff had a higher mean score (9.0; 4.84) compared to the machine operators (3.3; 2.21). The histogram of correct responses for each question is shown in Figure 4.

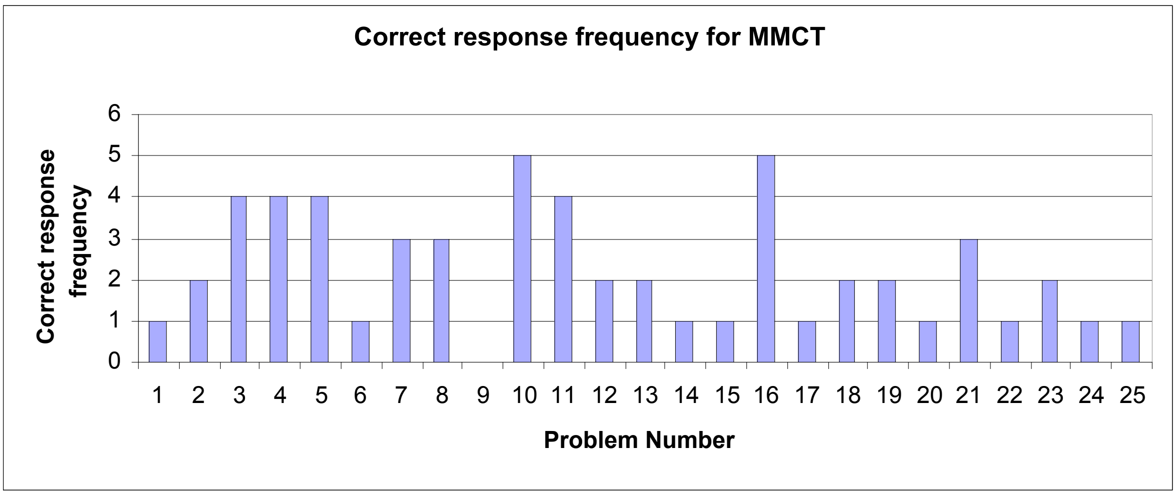

Figure 4. MMCT score distribution

Male participants scored a mean of 8.33; females scored a mean of 4.42. This is consistent with the findings of other researchers who use the MCT for testing spatial abilities.

The relationship between the duration of a worker's experience working on injection machines and their visualization skills, in this preliminary study, produced a correlation coefficient of -0.443 (figure 5). However, there is some evidence that a person's spatial skill reduces with age, so this negative trend may merely reflect this observation. This age effect is included in the distribution for the overall sample population (figure 6), where the contributions of gender and experience are combined. While the sample population now shows correlations of 0.53 for males and -0.47 for females, the small sample sizes mean that these interim results are not significant.

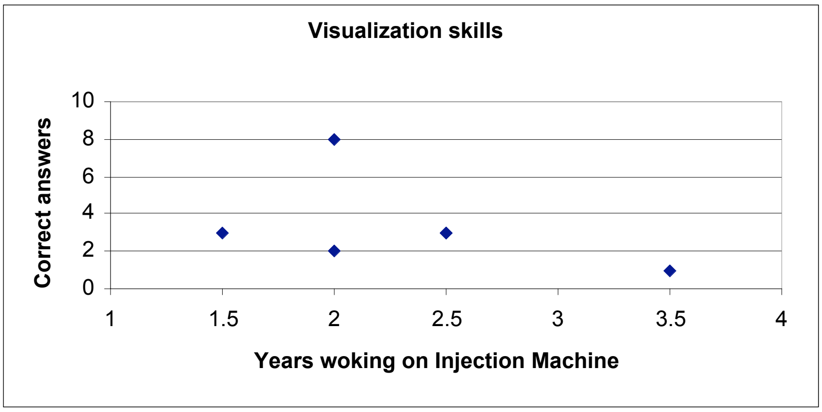

Figure 5. Machine operation experience compared with tested visualization skills

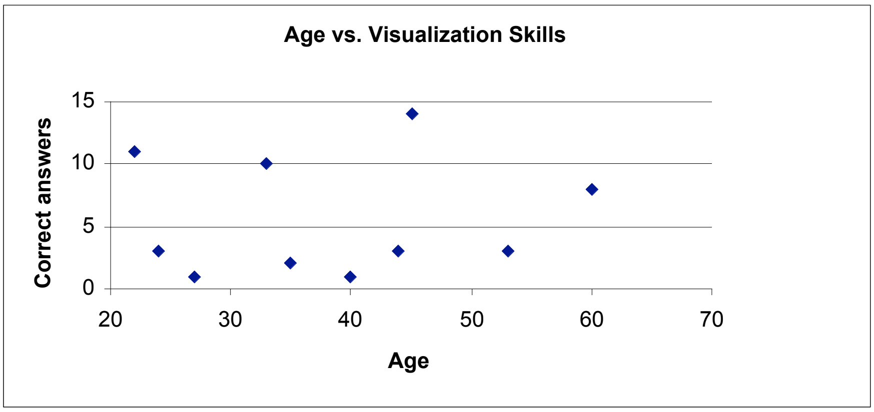

Figure 6. Sample population age versus tested visualization skills

3.4 Grouping of subjects for main study

Using MMCT and subject spatial skills as a basis, participants have been divided to two groups (figure 7). Group 1 was trained in 2D, with the use of paper based figures and representations, whereas group 2 was trained using a 3D representation of an injection mould.

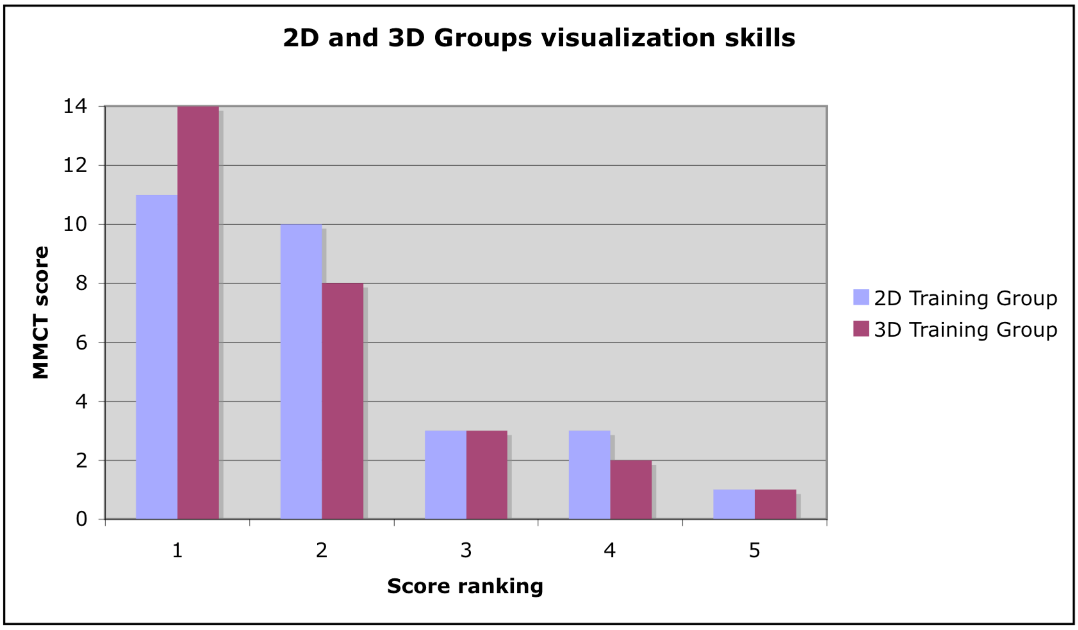

Figure 7. 2D and 3D training groups

4. An introductory training in injection moulding

Subjects were trained in injection moulding using two different methods. They were given a pre-test (Appendix A) prior to training, and an assessment (Appendix B) after the training session. Each subject was individually trained within a session, the common practice for on-site training.

Training was aimed to give the subjects the knowledge to:

- define the main systems of the injection mould;
- use proper terms for different features of injection mould;
- identify the interactions of mould features; and,
- be able to identify some mould features such as parting line and ejector pins, and their location by inspection of the moulded product.

The following features of injection mould were covered in the training session:

- parting surface;
- injection system;
- ejection system;
- draft angle;
- cooling system/heat exchanger;
- cavity layout and number of cavities;
- fasteners in the tool.

4.1 Training resources

1. Paper resource:
   A training resource had been prepared and used with the title "Introduction to Injection Moulding" (Appendix C)

2. Plastic parts:
   Some plastic products (figures 8 and 9) were used as training aids. Subjects were trained to find tool features such as the parting surface, gate location and ejector pins following close inspection of the product.

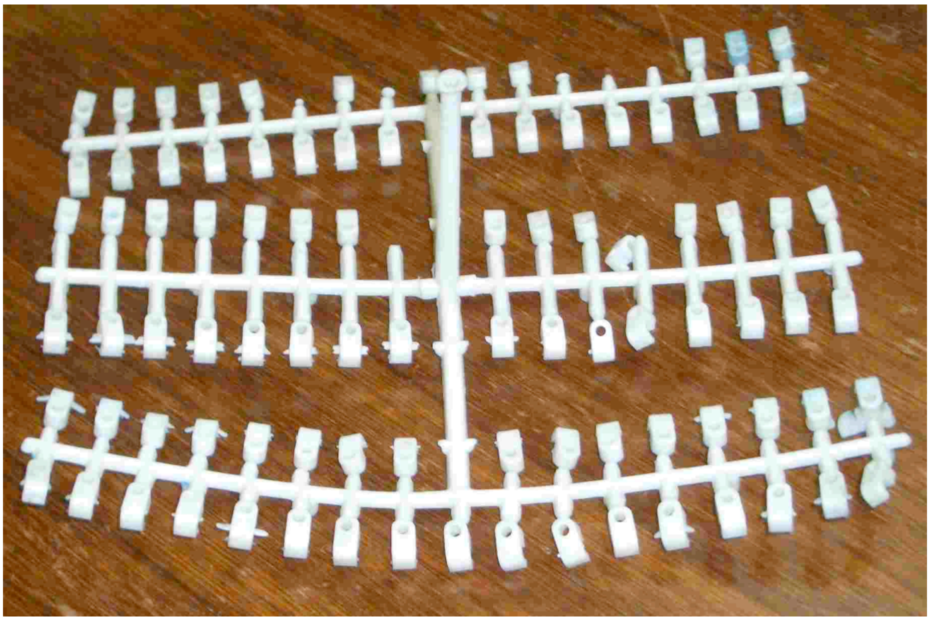

Figure 8. Multi-cavity mould featuring sprue, runner, and gate

Figure 9. Cup-shaped moulded part. Ejector pin and gate can be observed in the image.

3. 3D model:
   As an alternative to using pictures and drawings, a timber mould suitable for a cup-shaped product was produced and used in the training programme (figures 10 and 11).

Figure 10. 3D timber mould model for producing a cup shaped product. Mould closed.

Figure 11. 3D timber mould halves, showing the ejection system activated

The following arguments were developed to justify the suitability of a cup-shaped product for introductory training in injection moulding:

1. The geometry is easy to make.
2. Different logical gate shapes can be explained (training associated with balanced and unbalanced filling can be introduced).
3. Different important ejection systems (e.g. pins, bush, stripper plate) can be explained.
4. This shape is repeated in a large number of plastic products.
5. The shape introduces the use of different draft angles and how they affect the design.
6. By use of a pin gate, the 3-plate mould and hot runner concept can be introduced.
7. Balanced and unbalanced filling can be readily compared.
8. Weld lines can be introduced. These are a very important product defect.

However, there are limitations in the use of this shape in conjunction with a timber mould:

- Sliders can't be introduced. This item was not a major obstacle since the training is at an introductory level.
- A draft angle was not applied to the model (for ease of manufacturing). Real 3D products were used for explaining this feature.
- Significant product defects, such as sink marks, could not be explained using only a mould model.

4.2 Training results

The performance of the 2D and 3D training groups are summarised in figures 12 and 13, respectively.

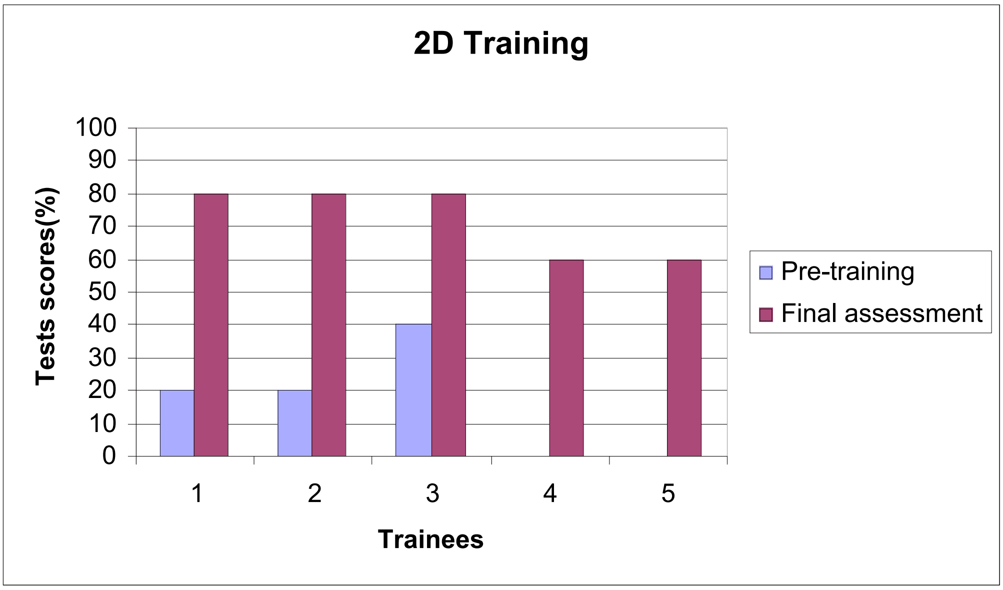

Figure 12. Training results for the 2D group.
Domain axis ranks trainees/subjects according to visualisation skill.

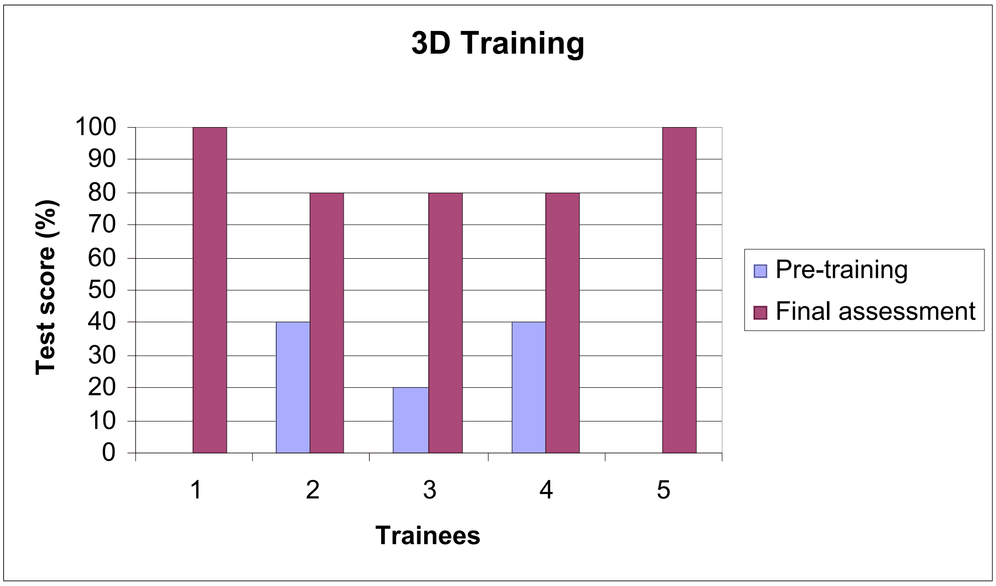

Figure 13. Training results of 3D training group
Domain axis ranks trainees/subjects according to visualisation skill.

The results in figures 12 and 13 are ranked according to visualization skills, with the first subject identified as being the most visual and the fifth subject the least visual in the group. When there is no column shown in the figure, the associated subject wasn't able to answer any questions in the MMCT test. The subject with the highest visualisation skill achieved the highest (or equal highest) available post-training assessment score in both groups. In particular, trainee-1 in the 3D training group (figure 13) scored zero prior to training but was able to achieve 100% in he post-training assessment. Figure 14 shows the frequency of correct response for all subjects to the five post-training assessment (sample question in Appendix B).

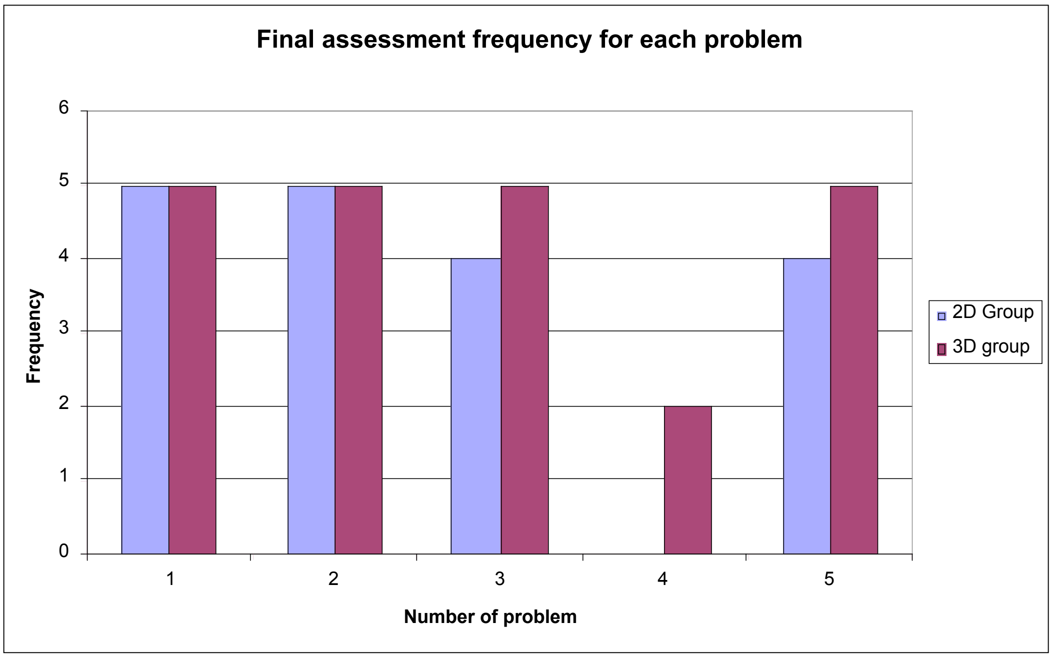

Figure 14. Post-training assessment: frequency of correct answer for each of the five questions asked (sample question included in Appendix B – question 4 of 5).

4.3 Training observations

The lack of prior training and basic knowledge of the equipment and processes that workers are asked to operate, are common characteristics of the workers engaged in the formal training programme introduced in this paper. For the preliminary sample of six workers, this is irrespective of the number of years spent working on different machines. Key training observations:

Training resources:

1. All trainees found MMCT difficult. The long test duration (20 minutes) could be one of the reasons why it was hard for trainees to concentrate on the test. The production imperatives of the company were distracting to the factory workers (training and testing were completed on-site).
2. All trainees started each test with low confidence.
3. "Parting surface", its importance and selection, were the most difficult concepts to the trainees under training. It appears that there should have been more samples and figures associated with training subjects about parting surface. An important outcome in preparing for the full study.
4. Question 2 in the pre-competency (pre-training) test was the hardest question for trainees to understand and answer. None of the trainees could answer this question.
5. The hardest question in final assessment was number 4 (Appendix B). Trainees had difficulty visualizing the figure, understanding the question, and relating it to the cup-shaped product. They were trying to answer the problem on the basis of understanding the object, rather than abstracting the shape. In part-b of the question, they wanted to know the function of a hole at the centre of an otherwise very similar part. Based on the function of the part, trainees tended to answer differently to part-a and part-b, because the couldn't generalize the principle.

   It was suggested after the testing and training session that the subjects could have understood the products better had the images been rotated, and if the trainees had a context for the products, i.e. products used were similar to real cup-like objects that trainees experience in everyday life. This reflects the limited visualisation skills of the cohort. Half of the respondents tended to mark the opposite answer to the correct alternative.
6. The trainees had difficulty understanding the word "label" in one question in the post-training assessment. This was a sign of limited literacy capabilities and unfamiliarity with technical terms that are often used in written tests. Following this observation, trainees were recommended to simply cross or circle the correct alternative or item in the question (rather than "label" it).

Plant and process related observations – promising outcomes based on the personal training, assessment and review procedures used in this pilot study:

1. The trainees could anticipate production issues associated injection moulding after training. An enhanced understanding of the processes and the number of parameters involved was apparent. In addition, all six were more prepared to learn about the underlying issues associated with process problems that they would previously refer immediately to a supervisor.
2. The trainees were content with their familiarity of the terminology associated with mould technologies. They considered themselves were more confident after training in their ability to discuss problems with their supervisors, as they could use correct technical terms for various mould tool features.

3. The trainees who have had previous problems with a product feature, such as sprue sticking to the mould and not leaving the mould tool, asked many questions regarding that particular item and tried to analyze the problem more closely during training sessions. This highlights the advantage of on-site training in terms of facilitating the connection between practice and the underlying theory.
4. Some of trainees wanted to be clear in particular areas that were very advanced compared to the level of knowledge that the training was expected to provide, as agreed by management of the training organization and the plastics company. This showed deep insight from these trainees, and a motivation to gain additional understanding beyond that required for their current role.
5. During training with the 3D model tool, the model was referred to as a jig-saw puzzle. One of the trainees used the same term for the model as he used to describe his interest in brain teasing ‘puzzles’. This observation will be used in the full trial in an attempt to introduce the training as, in part, a “game playing” exercise. It is hoped this approach will assist the engagement of future trainees with the learning material.
6. Office staff had enjoyed their training session. They considered it important for their interactions with clients.

Plant/process related observations – upsetting outcomes based on the personal training, assessment and review procedures used in this pilot study:

1. Some of the factory workers (machine operators) offered a negative, often emotional, response after the testing and training programme when they realized their prior lack of understanding of the issues associated with the job they have been doing for a number of years.
2. Four of the machine operators stated that their supervisors, historically, did not respond favourably when asked for information about the process and equipment to be operated. One factory worker was accused of being a ‘trouble maker’ because of the questions being asked – reportedly, the same questions being answered in this training and evaluation programme. This issue will be investigated further in the main study.

5. Conclusions and recommendations

1. Prior to this research, the MMCT has been mainly used on university students. Based on test results with university students reaching a mean score of 15 [9], the training sample population has lower visualization skills, achieving a mean of only 6.
2. There is a correlation coefficient of 0.426 between the level of education and visualization skills of the preliminary sample population. Administration staff had higher visualization skills compared to the available machine operators. This could adversely affect attempts at pictorial communication in the main study.
3. Male subjects had better visualization skills than female. This reflects previous results from similar tests [10]. This is important since workers in the Australian plastics industry sector are largely female, compared to metals industry that is male dominated.
4. The effect of age on visualization skills was different for men and women. This preliminary outcome will be further explored.
5. Years of experience working on the factory floor did not appear to improve visualization skills.
6. Since a significant component of standard IQ tests includes visualization questions, it can be anticipated that the sample population includes subjects of low IQ, and it is expected

that this will affect communication by all of graphical, verbal and written forms – as distinct from 3D model based activities.

7. The MMCT was extremely difficult for the sample population to read and understand. It is recommended that a simpler test be used for the main study. The subjects often wanted to know of any methods they could use to develop visualization skills.
8. The use of 3D training methods instead of 2D representations was found to be more efficient for learning by the sample population. The differences between the 2D and 3D training approaches, and how they affect learning outcomes, appeared to be more significant when educating people with lower visualization skills. The 3D model identified in figure 1 was not used in the preliminary study reported in this paper as there were concerns that its design, based on maximising the number of design features in a single product, could overwhelm subjects. The simplified 3D model (figure 10) was a very successful learning tool and the full study also use the more sophisticated model.
9. Another problem associated with 2D training in the vocational (pre-university) sector is the low level of literacy skills of many of the people to be trained. Long and erudite written training resources were not found to be an effective training medium.
10. The use of other training methods such as tactile training, or use of stereographic images and animations, and how these methods affect learning outcomes of the trainees, will be a consideration for the full study.
11. As engineering graphics education has been shown to improve spatial skills [9], it is recommended that similar units be added to polymers training schedule for non-tertiary students.

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Appendix A. Sample problem from training pre-test

3. Which letter points to the "sprue bush" in the following schematic section (figure 3) of an injection mould?

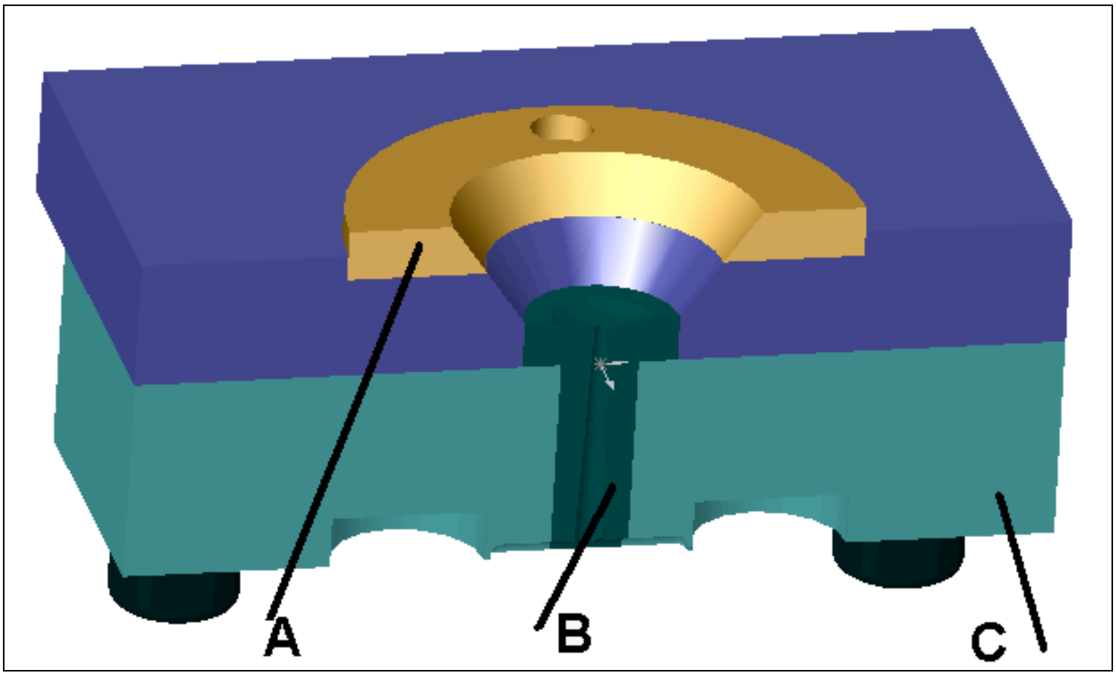
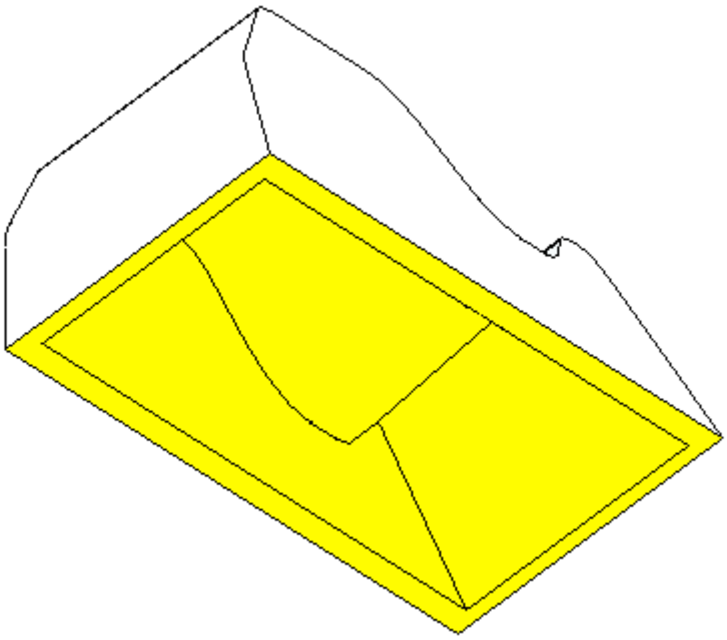


Figure 3

Appendix B. Sample problem from training post-test

4a. Based on figure 4 which surface(s) of the parts are shaped by the moving (ejection) half?
(Circle the correct color.)



Qn 4a. Yellow or White ?

Figure 4

Appendix C. Sample information from the 2D training material

Figure 2 shows a typical injection mould. The injection mould consists of two halves: moving and fixed, which meet at the parting surface.

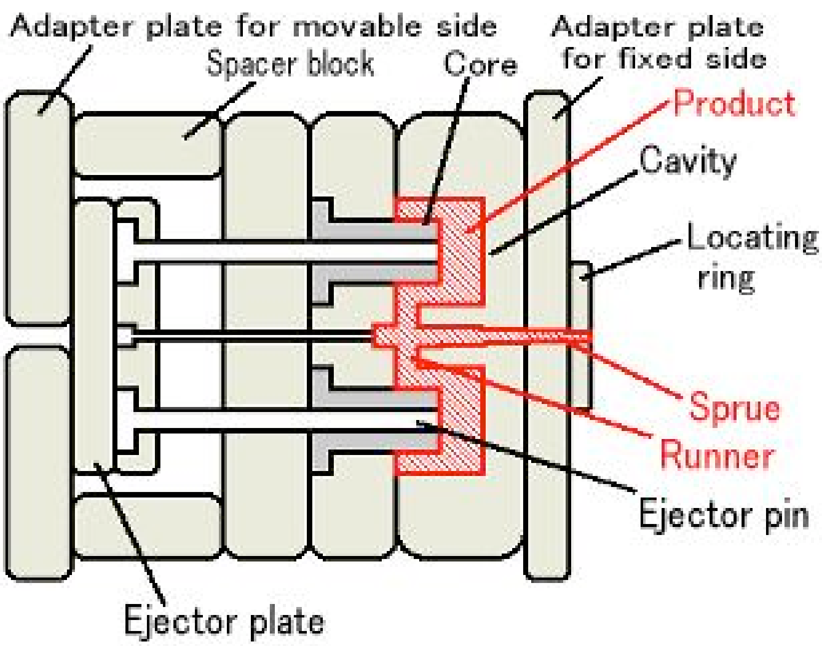


Figure 2: A typical injection mould