Iowa State University

From the Selected Works of Michael C. Dorneich

December 20, 2016

Design and Evaluation of Designer Feedback System in Design for Manufacturability

Prashant Barnawal, *Iowa State University*

Michael C. Dorneich, *Iowa State University*

Frank E. Peters, *Iowa State University*

Matthew C. Frank, *Iowa State University*

Available at: https://works.bepress.com/michael_dorneich/51/

Design and Evaluation of Designer Feedback System in Design for Manufacturability

Prashant Barnawal, Michael C. Dorneich, Frank Peters, Matthew C. Frank
Industrial and Manufacturing Systems Engineering, Iowa State University

The aim of the study is to develop and evaluate a prototype designer feedback tool to give manufacturability feedback information to design engineers early at the conceptual design stage. Providing design engineers early manufacturability information on their designs helps them to improve manufacturing quality of their designs thus reducing the overall cost and lead time to manufacture. The Three Dimensional Integrated Feedback (3DIF) system is designed to be a manufacturing visualization feedback tool that is generalizable, automated, usable, inexpensive and portable. Feedback given to design engineers can be in various modalities, including verbal, text, 2D drawings, or 3D. Information abstraction and modality significantly affect its interpretation, so it is important that feedback given to the design engineers should be in the language understandable to them and is able to convey necessary information with minimal interpretation. An experiment has been designed to evaluate performance and workload differences between expert and novice design engineers when they conduct design tasks in feedback modalities.. The preliminary results from the study show that providing feedback in 3D improves the manufacturing quality of the end design with lower overall cognitive workload.

INTRODUCTION

Manufacturing industries today have grown large and spread across distant geographical locations. This has led to formation of distributed teams with specialized knowledge. The distributed nature of operation hinders information flow and communication between functional teams. The close collaboration that used to exist in the past has diminished over the years. For example, product design engineers operate separately from the manufacturing engineers, in different departments and often in different locations. The functional roles of the two are largely different.

In a traditional “throw-it-over-the-wall” approach design engineers focus on meeting the functional requirements of the products with less focus on its manufacturability processes, cost, and time to manufacture (Lardner, 1992). Manufacturing engineers, on the other hand, focus on the manufacturing processes that turn the conceptual designs into finished products. Designs may meet functional requirements but be difficult or infeasible to manufacture. To improve the manufacturing quality of the designs, design engineers rely on manufacturing engineers to review their designs and give them manufacturability-related feedback (Mohammed, May, & Alavi, 2008; Lardner, 1992). It takes multiple iterations before designs are ready to be manufactured. This process can significantly delay development. The design process in North America can take up to 2 years and 15 to 20 years for military vehicles from the conceptual stage to the production period (Kim & Simpson, 2013). The conceptual design phase is very critical because important decisions related to product designs are made at this stage. Changes in the product design phase incur very little cost relative to the overall project but can determine a significant percentage of the total production cost (Anderson, 2014; Ferreira & Hubka, 1993). Any changes made in later phases can be very expensive.

Design for Manufacturability (DFM) is a technique to bring the knowledge of manufacturing early at the conceptual design stage to the design engineers (Wheelwright & Clark, 1993). DFM provides a set of standard guidelines, specific to manufacturing processes, to follow while designing. Several automated DFM tools have been developed that evaluate designs and give scores or feedback to the design engineers (Gupta, Regli, Das, & Nau, 1997). The scores or feedback helps design engineers to improve the manufacturing quality of their designs. The purpose of the DFM tools is to perform robust analysis of the design and provide easy-to-understand feedback to the design engineers. Boothroyd and Dewhurst (1983) developed Design for Assembly (DFA) guidelines, which have been used by many other automated tools (Gupta, Regli, Das, & Nau, 1997; Li & Hwang, 1992). Gupta, Regli, Das, & Nau (1997) argued that improving the output format could have provided design engineers more information. Warnecke and Bassler (1988) studied functional and assembly characteristic of a component. If a component has low functional value but high assembly cost, it received low scores, whereas, component with high functional value and low assembly cost was scored high. The scoring strategy was used to make redesign decisions. Today, several state-of-the-art analysis tools like Autodesk’s Simulation DFM (Autodesk, 2013), DFMPPro (DFMPPro, 2012), Boothroyd and Dewhurst’s DFM Concurrent Costing tool (DFM Concurrent Costing, 2014) perform complex manufacturability analysis and give feedback to design engineers. Feedback given to the design engineers can have varying levels of data abstraction and be in several modalities like text, 2D, 3D or complex simulations. Boothroyd Dewhurst’s DFM Concurrent Costing tool provides manufacturability cost and time information in tabular format along with 2D charts. DFMPPro can integrate with CAD tools and provide colored manufacturability 3D feedback within the CAD environment. It also generates portable 2D and text reports.

Design engineers are not manufacturing specialists. It is important that manufacturability information given to them should be in a language understandable to them. Many manufacturing and architecture industries still make use of traditional paper and 2D engineering drawings to convey design intent (Gott, 2003; Lubell, Chen, Horst, Frechette, & Huang, 2012; Opsahl, 2013). Studies have shown that modality of information affects performance and workload of humans (Cao, Theune, & Nijholt, 2009; Tavanti & Lind, 2001; Kashiwara, 2009; Gîrbacia, 2012). Two-dimensional drawings can be ambiguous and can lead to multiple three-dimensional interpretations (Butler, 1982). Architects differ in their abilities to mentally visualize in 3D. Yagmur-Kilimci (2010) concluded that being able to mentally visualize buildings in 3D required people to have architecture-specific knowledge. Kashiwara (2009) and Gîrbacia (2012) evaluated cognitive workload of interpreting and mentally imaging 3D model from 2D drawings. The performance of the participants was measured in terms of reaction time and accuracy. Results showed that 3D mental imaging from 2D drawings was less accurate and the reaction time needed was high because mental 3D imaging required more working memory. Gîrbacia (2012), however, argued that the benefits of 3D visualization for very complex engineering drawings may not be significantly higher compared to its 2D counterpart.

In order to cut down the iterative cycle between design and manufacturing engineers it is important that automated DFM tools are used early in the design process that give comprehensive feedback to design engineers. Being able to correctly visualize the feedback information will aid design engineers to quickly learn and reason about different tradeoffs to consider while designing. Case studies of visualization tools in realistic work settings are the least common types of studies performed (Plaisant, 2011). Many new DFM tools like CNC-ana and Cast-ANA (Traband, 2013) are being developed; being able to give comprehensive feedback in the correct modality will increase their benefits and acceptance by the users. The Three Dimensional Integrated Feedback (3DIF) tool was developed to provide manufacturing feedback that is generalizable, automated, usable, inexpensive and portable. This paper describes the development of 3DIF and presents an ongoing study to investigate the performance and workload effects of different modalities of feedback with engineering students in casting and professional casting design engineers at their workplace. The evaluation design is described, with preliminary results presented. The study aims to provide empirical evidence about the helpfulness and usability of the approach in the actual work scenario.

THREE-DIMENSIONAL INTEGRATED FEEDBACK (3DIF) TOOL

The motivation behind development of the Three Dimensional Integrated Feedback (3DIF) tool was to develop a manufacturing feedback system that is generalizable, automated, usable, inexpensive and portable. 3DIF uses portable document format (PDF) as an underlying format. Using PDF makes 3DIF portable across various digital devices and also easily shared over the web because of its manageable

file size. 3DIF users do not require proprietary CAD or DFM tools to visualize it. They can use Adobe Acrobat reader which is available free of cost, this makes the feedback inexpensive. The software that generates 3DIF is not confined to a particular type of manufacturability process but can be generalized to generate feedback for several different processes like casting, machining and welding. 3DIF gives feedback as colored 3D data with other supplementary information.

Currently, 3DIF is used with casting analysis software called Cast-ANA (Traband, 2013) and machining analysis software called CNC-ana (Traband, 2013), which perform multiple analyses related to a particular manufacturing process and embed multiple results in a single document in their respective feedback window. Each analysis window is divided into two parts, one that shows colored 3D data as feedback and the other provides supplementary information. Figure 1 shows 3DIF generated by Cast-ANA software when STL model is provided as an input. The four feedback windows in 3DIF correspond to four different types of casting analysis done by Cast-ANA on the input model. The model in each of the window is colored yellow and the region of interest is marked with different colors to distinguish it from the rest of the model.

Figure 1: 3DIF feedback from CAST-ANA of the above model.

The four windows shown are Constant Cross Section (CCS) analysis (Top-Left), Isolated Heavy Section (IHS) analysis (Top-Right), Visibility (VISI) Analysis (Bottom

Left) and Core area analysis (Bottom Right). CCS regions are shown as red solid surfaces. These regions could have potential metal feeding problems due to hindrance in directional solidification process. Directional solidification rule states that casting should cool and solidify progressively from thin-sections to heavy sections with constant liquid metal feed to the heavy sections (sfsa, 2005). CCSs have uniform thickness throughout which results into uneven cooling and solidification. This causes porosity and cavities in those regions. To avoid CCS and promote directional solidification, the design needs tapering in the correct direction in those regions. IHSs are shown with the help of red solid spheres. These are regions of high volume that will require metal feeders to feed liquid metal during metal solidification stage. The location of the sphere shows the location of the feeder and the size of the sphere shows the volume of the feeder needed in those regions. IHSs solidify the last; it requires a constant supply of liquid metal during solidification to compensate for cooling shrinkages. Setting up metal feeders is expensive and requires post machining to clean up the surface. A design with less number of IHSs is a preferred design in casting. Visibility is shown with colored cones; the green cones indicate the primary orthogonal axis about which the surface visibility is the maximum. It indicates a possible direction, called the parting direction, about which casting could be performed. The Core analysis window shows the cores, additional structures needed to cast inner cavities, re-entrant angles etc., that will be needed to cast a part about one of the three primary orthogonal parting directions. Cores with X axis as parting direction is shown as red solid, Y as green and Z as blue. Cores corresponding to a parting direction can be turned on and off with the help of check boxes provided. Setting up cores can be expensive. A design with lesser number of cores is a preferred design.

Having all the analysis windows integrated in a single document will allow design engineers to both isolate one result from the other and also visualize one result in the context of the others. This would help them make better redesign decisions. For e.g. a design change to eliminate isolated heavy sections could lead to introduction of core regions and vice-versa. Visualizing both the feedback simultaneously can assist design engineers to consider similar tradeoffs when they redesign the part.

METHOD

Research Objective

The study aims to investigate the performance and workload tradeoffs when considering different modalities of feedback with the expertise level of the design engineer. The results gathered from the study will help improve the design, usability, and usefulness of 3DIF.

Hypotheses

Hypothesis 1. Providing early manufacturability feedback in any modality will help both novice and expert designers reduce more manufacturability imperfections compared to no feedback.

Hypothesis 2. 3D feedback will help design engineers redesign faster, eliminate more total imperfections, and with less cognitive workload compared to the other modalities of feedback.

Hypothesis 3. The design time, quality and workload benefits of 3D over other modalities will be higher for novice design engineers than expert design engineers.

Participants

A total of 30 participants are expected in this on-going study. As of the submission of this paper, two subjects have been run. The first two subjects were male undergraduate engineering students who had experience with casting design. The expert had 3 years and the novice had 6 months of casting experience. Preliminary results are presented at the end of the paper. Final results will be made available through supplementary materials.

Tasks/Scenarios

Participants were given a 3D CAD model of a bracket part to redesign and improve its casting quality. Four different parts were developed with design errors introduced in them and are of equal complexity for every trial. The complexity of the model was based on the type of the features they had and the complexity of redesign needed to eliminate the non-preferred features. The models contain some design errors which are easily visible (e.g. surface undercuts for Cores) and some errors which are subtle and difficult to visualize (e.g. inner cavities or small negative drafts). These features can have interaction effect among themselves; for instance eliminating isolated heavy sections can introduce constant cross-sections. Depending on the experimental condition, participants were either provided with one of the three feedback or no feedback. Participants were asked to follow the same design constraints when they redesigned the model. They were not allowed to use any other tool to check for constraint violations instead they had to apply their design expertise to estimate any violations. They stopped their trial once they were satisfied with the final design.

Independent Variables

There are two independent variables in the study, *Design engineer expertise* (novice, expert) and *Modality of feedback* (none, text-based, 2D, and 3D). The experts and novices are determined based on their response to a questionnaire related to their experience as casting design engineers and knowledge of casting process. Casting analysis feedback was produced by Cast-ANA software package. The text feedback was given as pdf document having analysis information in tabular format; the 2D and 3D feedback were similar, where in 2D, the 3D rotations were disabled on the models. The participants can only switch the model to predefined standard views, Top, Front, Left, Right, Back and Bottom.

Dependent Variables

The dependent variables are summarized in Table 1. *Performance* is measured in terms of time taken to redesign the

original model and overall cost reduction of the final design. The final cost is cumulative cost of the old errors eliminated and new errors introduced. The time and cost is measured once for every trial. *Workload* is measured based on NASA-TLX survey after every trial. *Confidence in the redesigned model* and *Comprehensiveness of feedback* are measured with Likert scale response of the participants after every trial.

Table 1. Dependent Variables.

Dependent Variable	Metric	Frequency
Performance	Time to re-design model	once per trial
Performance	Total Cost reduction of the model	once per trial
Performance	Errors reduced or eliminated	once per trial
Performance	New Errors introduced	once per trial
Performance	Design constraints violated	once per trial
Workload	NASA Task Load Index	once per trial
Confidence	Likert Scale 1-5	once per trial
Comprehensiveness	Likert Scale 1-5	once per trial

Experimental Design

The experiment is a 2 (expertise level) by four (feedback modalities) mixed subject design. The expertise level is between-subject and feedback modality is with-in subject. Each subject conducted four trials, once each in no, text, 2D, and 3D feedback. The sequence of the models and feedback conditions was randomized for every participant in order to reduce any learning effect on the actual data.

Procedure

The participants began the study by reading and signing a consent form. Next, the participants filled out a preliminary questionnaire after which they underwent training session. Participants were trained on the casting imperfections, feedback, CAD features they were allowed to use, and how information about the casting imperfections was shown in each of the four modality conditions, the approximate design scoring or cost model to help them to decide between design trade-offs, and the design constraints of the parts they were redesigning. Training was conducted until they were comfortable with and had demonstrated (through questionnaires) that they were competent in all aspects of the study, and had a chance to conduct a training trial to familiarize themselves with the re-design task. After training, they conducted four design trials. Each trial was followed by a post-trial questionnaire and workload survey. After the completion of all the trials, the participants filled out a post-experimental questionnaire and debriefed about the 3DIF tool.

Data Analysis

The data collected will be first tested for normality. A Mixed Two-way ANOVA test will be performed on the data for each modality of feedback and both levels of expertise. This will help us find out the modality which is most statistically significant to improving the cost of the design and time taken to redesign. We will be doing similar tests for measuring the workload associated with each feedback modality. The mixed ANOVA will also help us discover the

underlying interaction of user-expertise-level and feedback modality

PRELIMINARY RESULTS

Time Taken to Re-design the Model

The expert took less time in the redesign task than the novice across all modalities. Differences between modalities were inconclusive.

Total Cost reduction of the model

Figure 2 shows the percentage change in cost. Although, 3D feedback improved the cost of the final design compared to the other modalities of feedback, the improvement was less than the no-feedback scenario.

Figure 2: Percentage difference in cost

Original Errors Reduced or Eliminated

Across all modalities, the expert and novice both reduced 8 of 10 errors. The expert subject eliminated more numbers of existing errors when feedback was given in 2D and 3D. The novice eliminated more numbers of errors in 2D and in no-feedback scenario.. Overall, the expert reduced an average of 6.5 out of 10 existing design errors across all feedback modalities and the novice reduced 5.5 out of 10.

New Errors Introduced

Overall, the expert introduced an average of 5.75 new errors across all modalities and the novice introduced 5.5 new errors. The expert introduced the highest number of errors (11 new isolated heavy sections) when feedback was given in 2D. This decreased the overall cost improvement. The novice introduced the highest number of errors (5 isolated heavy sections and 2 cores) in text feedback scenario. The final cost of the design was a cumulative sum of the errors reduced and errors introduced.

NASA Task Load Index

The mental workload experienced by expert and novice was low when feedback was given in 2D and 3D compared to other feedback scenarios, as seen in Figure 3

Figure 3: Mental workload.

Comprehensiveness of Feedback

Figure 4 shows the comprehensiveness of the three modalities of feedback based on user scores. The participants rated 3D feedback as more comprehensive than 2D and text.

Figure 4: comprehensiveness of feedback

Confidence

The expert was "very confident" (5 on a scale of 5) in 2D and 3D, and was "medium confident" (3) in text and no-feedback. The novice was "very confident" in 2D, and was "medium confident" in 3D, text, and no-feedback.

DISCUSSION AND CONCLUSION

Our preliminary data indicates that 3D feedback improved the cost of the final design. However, cost improvement was better in the no-feedback condition. The expert subject eliminated more existing errors when feedback was given in 2D and 3D. Their confidence in the final design was also high for these modalities which indicated less guess work on the redesign. The novice eliminated more numbers of errors in 2D and in no-feedback scenario. However, the confidence level was rated low when no feedback was given, this is an indication that this improvement in the design could be more accidental than intended. Both experts and novices rated the 3D feedback as the most comprehensive modality. The average mental workload experienced by the subjects in 3D and 2D was lower compared to the text and no-feedback scenario. This result is consistent with our proposed hypothesis.

The trend in the data will be clearer as we run more number of participants. We expect to see an interaction

between feedback modality and designer expertise on the quality of the end design. We expect the results to be coherent with our proposed hypothesis.

REFERENCES

- Anderson, D. M. (2014). Design for Manufacturability: How to Use Concurrent Engineering to Rapidly Develop Low- Cost, High-Quality Products for Lean Production. CRC press.
- Autodesk. (2013). Autodesk Simulation DFM.
- Boothroyd, G., & Dewhurst, P. (1983). Design for assembly - a designer's handbook. Department of Mechanical, Engineering, University of Massachusetts,
- Amherst. Butler, D. L. (1982). Predicting the Perception of Three-Dimensional Objects From the Geometrical Information in Drawings. *Journal of Experimental Psychology*, 674-692.
- Cao, Y., Theune, M., & Nijholt, A. (2009). Modality Effects on Cognitive Load and Performance in High-Load Information Presentation. *ACM*, (pp. 335-344). New York.
- Design for Manufacturing and Assembly. (2015). Retrieved from DFMPro A Geometric Product: <http://dfmpro.geometricglobal.com/>
- DFM Concurrent Costing. (2014). Retrieved from DFMA: <http://www.dfma.com/software/dfm.htm>
- DFMPro. (2012). *DFMPro A Geometric Product*.
- Ferreirinha, P., & V. Hubka, W. E. (1993). Early cost calculation: reliable calculation, not just estimation..*Design for Manufacturability – ASME*, 85-90.
- Girbacia, F. (2012). Evaluation of Cognitive Effort in the Perception of Engineering Drawings as 3D Models. The Fifth International Conference on Advances in Computer-Human Interactions, 247-250
- Gott, B. (2003). *Evolution from 2D to 3D – a Design Engineer's Perspective*. Cambridge: Cambashi Limited, 1-8
- Gupta, S. K., Regli, W. C., Das, D., & Nau, D. S. (1997). Automated Manufacturability Analysis: A Survey. *Research in Engineering Design*, 168-190.
- Kashihara, K. (2009). Evaluation of the cognitive process during mental imaging of two- or three-dimensional figures. *Advances in Computer-Human Interactions*.
- Kim, W., & Simpson, T. W. (2013). Toward Automated Design for Manufacturing Feedback. *International Federation for Information Processing*, 40-47.
- Lardner, J. F. (1992). Communication Barriers to Effective Manufacturing. In *Manufacturing Systems Foundations of World-Class Practice* (pp. 173-179). Washington, D.C.: National Academies Press.
- Li, R.-K., & Hwang, C.-L. (1992). A framework for automatic DFA system development. *Computers in Industrial Engineering*, 403-413.
- Liker, J. M. (2006). The Toyota Production Development, *System*. New York: Productivity Press.
- Lubell, J., Chen, K., Horst, J., Frechette, S., & Huang, P. (2012). *Model Based Enterprise / Technical Data Package Summit Report*. National Institute of Standards and Technology.
- Mohammed, D. J., May, M. J., & Alavi, D. A. (2008). Application of Computer Aided Design (CAD) In Knowledge Based Engineering. *IJIC-IJME International Conference*.
- Opsahl, D. (2013). Visualization vs. Communication, Enabling the Model-Based Enterprise with 3DPDF. 3DPDF Consortium.
- Plaisant, C. (2011). The Challenge of Information Visualization Evaluation. *ACM*, 109-116.
- Tavanti, M., & Lind, M. (2001). 2D vs 3D, Implications on Spatial Memory. *IEEE Symposium on Information Visualization*.
- Traband, M. (2013). Using the iFAB Architecture to Execute Rapid Response Manufacturing. Gaithersburg: MBE Summit.
- Warnecke, H., & Bassler, R. (1988). Design for assembly - part of the design process. *Annals of the CIRP*.
- Wheelwright, S. C., & Clark, K. B. (1993). *Managing New Product and Process Development: Text Cases*.
- Yagmur-Kilimci, E. (2010). *3D Mental visualization in architectural design*. Georgia Institute of Technology.