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Design and evaluation of feedback system in design for manufacturability

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Design and evaluation of feedback system in design for manufacturability

by

Prashant Barnawal

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Human Computer Interaction and Computer Science

Program of Study Committee:
Michael Dorneich, Co-Major Professor
David Fernandez-Baca, Co-Major Professor
Matthew Frank
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Iowa State University

Ames, Iowa

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NOMENCLATURE

2D	Two Dimensional
3D	Three Dimensional
CAD	Computer Aided Design
3DIF	Three Dimensional Integrated Feedback
DFM	Design for Manufacturability
CNCRP-ana	Computational Numerical Control Rapid Prototyping Analysis
CAST-ana	Casting Analysis

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ABSTRACT

This research study evaluated the effect of different manufacturability feedback modalities on design engineers' ability to improve the manufacturability of their designs. A manufacturability feedback tool called the Three Dimensional Integrated Feedback (3DIF) has been developed and evaluated, the purpose of which is to provide manufacturability feedback information to design engineers early at the conceptual design stage. Conceptual design is an important factor which determines most of the overall manufacturing cost, resources and time, but design engineers are not manufacturing specialists. Providing early manufacturability feedback and suggestions to design engineers assist them to improve the manufacturability of their designs. Feedback given to design engineers can be in several modalities, most commonly verbal and textual. Studies have shown that mode of data representation affects its interpretability. Feedback information can be insufficient or difficult to comprehend which can lead to several design iterations and an increase in overall development time. An evaluation study was conducted with design engineers to evaluate how different feedback modalities affected their design performance, usability and workload. The results show that providing feedback in three dimensional modality significantly improved the design manufacturability with less mental workload compared to textual and no feedback. Providing textual feedback was no better than providing no feedback. This study will benefit manufacturing industries by demonstrating that easy-to-use, three-dimensional manufacturing feedback can significantly improve the design, increase usability, reduce workload, and lower the cost of the design process when design engineers are provided with it at a very early stage in manufacturing.

CHAPTER 1. INTRODUCTION

Critical decisions are made at the conceptual design stage in manufacturing (Saravia, Newnesb, Milehamb, & Gohb, 2008; Lipson & Shpitalni, 2000). Several parameters determining product manufacturability are determined and locked in at this stage. The conceptual design stage incurs the least project cost relative to other downstream stages but helps to determine a significant percentage of the total production cost (Anderson, 2014). Changes made to the designs after this stage can be very expensive or infeasible. However, design engineers are not manufacturing specialists. They lack critical knowledge related to suitable tooling, fixtures, machining processes and equipment needed to manufacture their designs (Zhu, Alard, You, & Schönsleben, 2011). Design engineers are mostly concerned with meeting the functional goals, and are often unaware of how designs impact manufacturing cost and feasibility of a product (Baba & Nobeoka, 1998). Manufacturability related information is possessed by manufacturing engineers. In order to achieve product goals related to functionality, manufacturability, aesthetics and human factors, design and manufacturing engineers should collaborate closely.

Effective collaboration results in teams successfully meeting time-to-market, cost and functionality goals. However, as project teams have grown larger and more distributed across distant locations, functional teams have evolved into small independent units which hinders in collaboration. Design and manufacturing engineers are seldom co-located (Huh & Kim, 1991; Cutkosky & Tenenbaum, 1992). Typically, design engineers create designs and "throw it over the wall", as shown in Figure 1, to the manufacturing team. Manufacturing engineers analyze the designs to determine the feasibility, cost, and manufacturing time. Manufacturing engineers give

feedback or suggestions to help design engineers improve the manufacturing quality of their designs. This process is iterative and slow in nature (Mohammed, May, & Alavi, 2008).

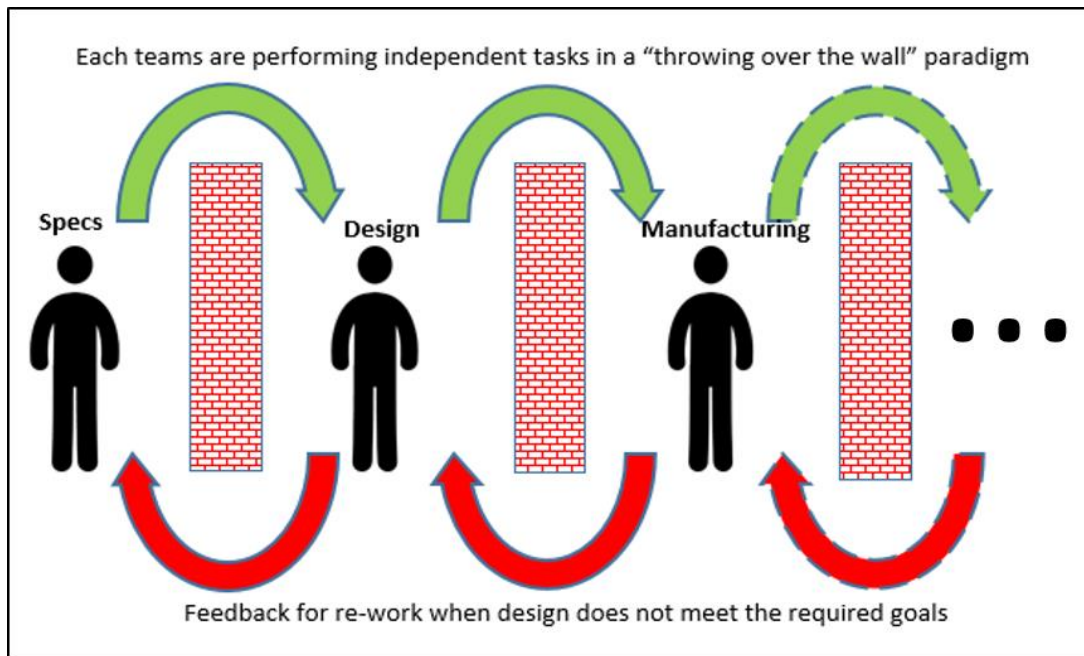


Figure 1: Design and manufacturing engineer collaboration in typical throwing over the wall strategy.

To alleviate the problems, Design for Manufacturability (DFM) techniques are employed by industries to bring manufacturability information to design engineers at an early stage. Figure 2 shows how design engineers follow DFM to improve the manufacturing quality of their designs. Instead of relying on direct feedback from manufacturing engineers, design engineers use automated DFM software tools that analyze designs and give them feedback about their manufacturing quality (Satyandra K, Das, & Nau, 1997). Design engineers interpret the feedback and redesign to improve the manufacturing quality of the original design. So, for feedback to be helpful, it is important that feedback given to design engineers should be in a language understandable to them.

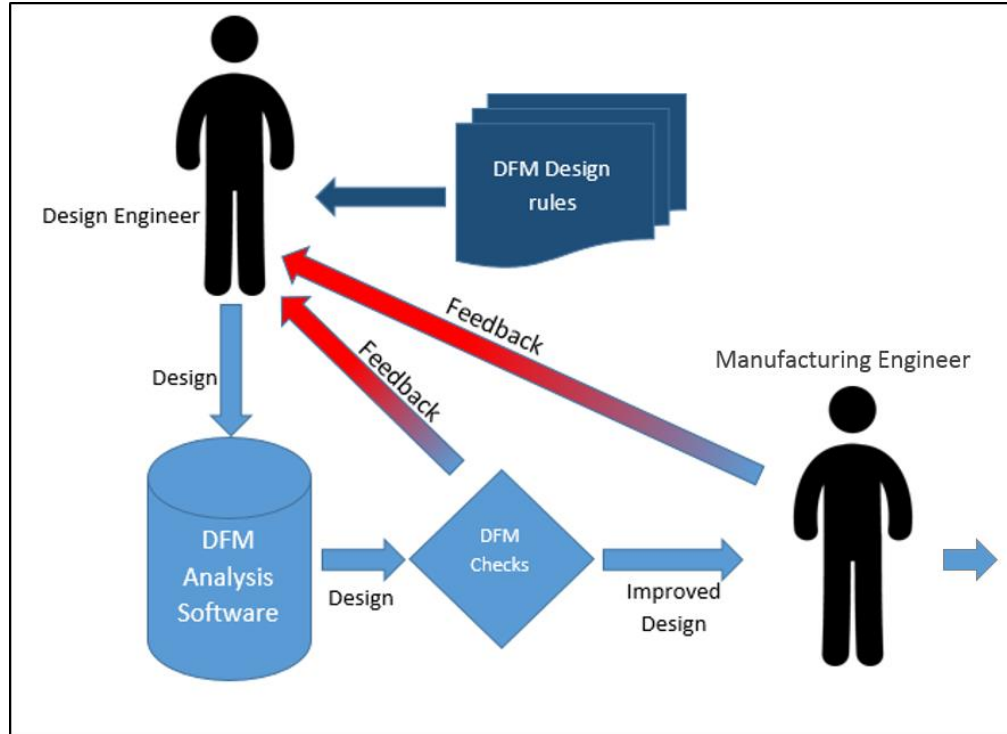


Figure 2: Implementing DFM at design stage to improve design manufacturability.

Manufacturability feedback given to design engineers at an early stage can assist them in early problem solving and decision making. Feedback information given to design engineers should be in a language that is comprehensible to them. Design engineers are concerned with physical and functional constraints. Any manufacturing feedback should be given in context to the part itself, so they can begin to incorporate manufacturing considerations in the part shape, for instance. Furthermore, if the manufacturing feedback is given in a form that is difficult to interpret, it is less likely to lead to an improvement in design. Finally, design engineers' design requirements and design strategies are largely dependent on their experience (Gobert, 1999; Kavakli & Gero, 2001; Ahmed & Wallace, 2004; Ahmed, Wallace, & Blessing, 2003), so feedback given to them should cater to the needs of design engineers across the spectrum of experience, supporting both novice and expert design engineers.

DFM techniques and tools that provide early manufacturability feedback exist in research today (Jones, Reidsema, & Smith, 2006; Madan, Rao, & Kundra, 2007; Lockett, 2005; Herrmann, et al., 2004). Feedback information provided by these tools have various levels of information abstraction and modalities. Some of the tools provide high-level information about the cost and time needed to manufacture the design, others provide detailed information about the expensive features in the design, and ways to re-design them. These tools use textual (Lockett, 2005; Madan, Rao, & Kundra, 2007), 2D (DFMPro, 2015) or 3D (Autodesk, 2015; DFMPro, 2015) modalities to provide necessary information. Although some software tools are moving towards advanced 3D visualization techniques to provide feedback, textual and 2D feedback are still commonly used in researches and industries. Providing effective feedback is an important component of DFM tools, however, most DFM researches are focusing on improving or introducing new manufacturability analysis algorithms (Quan, et al., 2013). Since, design engineers form an important component of any design cycle, it is important to find empirical evidence about how their design performance is affected by the modality of the manufacturability feedback given to them. Interpretability of information, in general, is dependent on the quality and the modality in which information is represented (Bauer & Johnson-Laird, 1993; Harrell, 2004; Easterday, Alevan, & Scheines, 2007). Thus, it is worthwhile to further investigate how feedback modality affects performance, usability, and workload of design engineers.

The aim of this research study was to evaluate the effect that modality of manufacturing feedback has on design engineers' ability to improve the manufacturability of their designs. A prototype manufacturability feedback tool, called the Three Dimensional Integrated Feedback (3DIF), was developed and evaluated. The purpose of the feedback tool is to provide design engineers with early, fast and usable feedback. The study evaluated how different modalities of

feedback affected design performance, usability, and workload of design engineers. Providing design engineers with usable feedback will streamline the overall design process, expediting the redesign process, and decrease the number of iterations to achieve high quality manufacturable design.

The rest of the thesis is organized as follows. Chapter 2 gives an overview of the background research related to the study. It describes visualization and DFM domains and why they should be combined to make usable DFM tools for design engineers in manufacturing. The literature review highlights how these domains have been extensively researched individually; however, the intersection of these domains remains an area of investigation. Chapter 3 gives an overview of the 3DIF tool and the automated software used to generate the content for 3DIF. Chapter 4 describes the experimental study design and the methodology. Chapter 5 presents the results of the study. Chapter 6 concludes with a discussion of the results and suggestions for future work.

CHAPTER 2. RELATED WORK

Visualization helps people to see things that are not obvious to them (Wijk, 2005). It promotes problem solving (Mendel & Yeager, 2010; Blaser, Sester, & Egenhofer, 2000) and decision making (Lurie & Mason, 2007; Kovalerchuk, 2001; Sackett & Williams, 2003) by exposing the underlying pattern within the data. The field of manufacturing benefits from visualization techniques; visualization is used as a primary means to communicate product design intent between functional teams with differing needs, but are driven by the same data set (Rohrer, 2000). Lack of proper communication can lead to project failures (Pritchard, 2004), so it is highly important that the sender sends information understandable to the receiver (Bergström, 2007). To design and analyze complex engineering drawings, design engineers rely heavily on software tools. The intent of Design for Manufacturability (DFM) software tools is to provide design engineers with automated and early manufacturability feedback on their designs (Satyandra K, Das, & Nau, 1997), with the goal of improving their manufacturability. DFM tools can exploit modern visualization techniques to give usable, comprehensive and possibly adaptive feedback. Modality and quality of information representation affect interpretability and, consequently, the performance of its users (Kashihara, 2009; Gîrbacia, 2012; Cheema & Bagchi, 2010). However, simply employing a graphical technique to display all the information may not assist its users in their particular tasks (Tory & Moller, 2004). To be able to exploit the power of visualization, it is important to understand the user tasks and needs (Sackett, Al-Gyaylani, Tiwari, & Williams, 2006). Case studies of visualization tools in realistic work settings are one of the least commonly performed studies (Plaisant, 2011). Shneiderman and Plaisant (2006) encouraged visualization researchers to study users performing tasks in the process of achieving their goals. They encouraged the use of observations, interviews, surveys, and automated logging of information to assess

user performance and interface usability. The aforementioned principles of evaluation of visualization tools can be used to address the usefulness of effective visualization in the field of DFM.

The remainder of this section provides an overview of related work in visualization design principles and challenges, DFM analysis tools and implementation of visualization in DFM, and studies related to modality and visualization. The various themes are consolidated to motivate the user study of 3DIF.

Visual Representation of Data

In manufacturing, visualization is commonly used to perform activities such as digital pre-assembly, human factors analysis, or design inspections (Opsahl, 2013). Visualization is defined as a mapping or binding of data to a representation that can be perceived in any form. This presentation form could be visual, auditory, tactile, or a combination (Ribarsky & Foley, 1994). Visualization is also commonly defined as “the use of computer supported interactive, visual representations of data to amplify cognition” (Card, MacKinlay, & Shneiderman, 1999, p. 6).

Visualization amplifies cognition by 1) increasing memory and processing resources because visualization takes the load off of memory and exploits human visual processing capabilities 2) reducing the effort to search for information 3) using visual representation for pattern detection iv) encoding information in an interactive medium (Card, MacKinlay, & Shneiderman, 1999). A large part of the human brain has evolved to process visual information (Segaran & Hammerbacher, 2009). Automated software algorithms designed to find trends in data are limited in their capabilities because they do not possess the same level of exploratory or reasoning skills as humans. Visualization techniques leverage human cognitive and visual processing abili-

ties to convey underlying behavior or pattern within the data (Weiwei & Huamin, 2007). Visualization aids users to gain useful insight by helping them build an interconnected mental model of the information, thereby, enabling the users to interpret and reason about the data, which otherwise may not be very intuitive, in less time (Purchase, Andrienko, Jankun-Kelly, & Ward, 2008; Faisal, Cairns, & Blandford, 2007).

Understanding how visualization exploits human perception capabilities, will enable the design and evaluation of feedback tools from users' perspective. This leads us to understanding more about some of the key principles of visualization design.

Visualization Design

To develop a usable visualization tool, it is critical to understand the underlying key principles of visualization design. Information visualization is a user-centered design discipline (Pretorius & Wijk, 2009), however, designers of visualization techniques should also give careful consideration to the underlying data that visualization tool represents. The key steps of designing well-disciplined visualization are as follows (Chittaro, 2006):

- 1) *Mapping*: how data objects and relationships are mapped to their visual counterparts.
- 2) *Selection*: presenting the right amount of information needed for a task.
- 3) *Presentation*: how do we present the information in the limited space?
- 4) *Interactivity*: interaction enhances the data exploration abilities of its users.
- 5) *Human Factors*: users should be able to quickly recognize and interpret the information being presented.
- 6) *Evaluation*: visualization effectiveness should be tested on users.

The design of 3DIF follows the above Chittaro's design principles. The evaluation of 3DIF, with design engineers performing their tasks with it, is an important step to understanding its usefulness in the context of the early design stage.

Challenges in Visualization Design

Despite the aforementioned benefits of visualization, building an optimal visualization tool for any data-set is not simple (Dadziea, Lanfranchia, & Petrelli, 2009). There are several existing challenges in visualization design that needs to be addressed. It is easy to make visualizations that are confusing and that can inadvertently miscommunicate information. Misinterpretation of visualization can result into catastrophic disasters. For example, in the Challenger Space Shuttle incident (Hastings, 2003) that killed seven astronauts, Tufte (1997) redesigned and analyzed the graphs used by the engineers and claimed that if the engineers visualized the data more effectively it would have exposed the risk of launching the space shuttle in cold weather. Some (Robison, 2002) argue that Tufte's reasoning was flawed, and the engineers were not responsible for the accident. They argued that Tufte misinterpreted the engineers' position and presumed that they had all the necessary data, but this assumption was incorrect. Common challenges facing researchers in visualization include: identifying user requirements, presenting the right amount of information so that superfluous information is hidden and only relevant information is presented, and evaluation and usability testing of the tools (Chen, 2005; Dadziea, Lanfranchia, & Petrelli, 2009).

In manufacturing, it is crucial to detect defects and solve the problems early. Implementing effective visualization techniques in DFM tools can help design engineers in early problem detection and elimination.

Visualization in Design for Manufacturability

Manufacturing, a sub-domain of engineering, relies heavily on visualization techniques (Rohrer, 2000). Two dimensional (2D) sketches and three dimensional (3D) models are used to convey complex design-related information. Visualization is a very common medium of communication and collaboration between functional teams. Manufacturing industries have grown very large and are geographically distributed across large distances. For example, Apple products are designed in California, U.S.A, but are manufactured in Mongolia, China, and Korea (Kabin, 2013). The distribution of personnel and capabilities has led functional teams to work independently of each other and build their own specialized knowledge.

Design for Manufacturability (DFM) principles have been developed to bridge the gap in information. In the past, DFM was commonly achieved through an iterative spiral design process in which marketing experts, manufacturing experts, design engineers and other personnel jumped back and forth between identification of customers' needs, design of products, and assessment of manufacturing issues (Satyandra K, Das, & Nau, 1997). Today marketing, manufacturing and design departments have evolved as separate organizations in a distributed manufacturing paradigm. Design engineers are less knowledgeable about manufacturability of their designs. The major role of design engineers is to make their designs meet the functional requirements with less regard to the other downstream manufacturing processes (Baba & Nobeoka, 1998). The manufacturability assessment of the design is done by manufacturing engineers at the shop floor (Mohammed, May, & Alavi, 2008). The design engineers are dependent on the manufacturing engineers for analyzing their designs and getting feedback or suggestions on the changes needed to further improve their manufacturability. The geographical distance between the teams hinders

communication and makes the review process slow and increases the number of iterations (Mohammed, May, & Alavi, 2008). It has been reported that design process can take up to two years in North America (Kim & Simpson, 2013). DFM is a technique designed to bring manufacturability information to the design engineers early at the conceptual design stage (Anderson, 2014). This enables the design engineers to evaluate the manufacturability quality of their designs without completely relying on manufacturing engineers. DFM introduces set of guidelines or rules to follow to improve the manufacturing quality of the designs. Design engineers work with advanced Computer Aided Design (CAD) and DFM software tools. These software tools can perform manufacturability analysis on the designs and give feedback or suggestions just like the manufacturing engineers. It is expected that success of DFM tools will largely depend on robust analysis of designs and the usability of their feedback. Novel visualization design and interaction techniques can be used with DFM tools to give comprehensive and useful feedback to design engineers.

Design for Manufacturability Tools

Automated DFM tools have been an active area of research and application for many years (Satyandra K, Das, & Nau, 1997; Bogue, 2012). Many manufacturing industries use them intensively as a means to save cost and time (Das, 2005). DFM tools vary in their scope and analysis methods.

Boothroyd and Dewhurst (1983) developed Design for Assembly (DFA) guidelines that many of the automated DFA tools use today. Some of the systems followed these assembly guidelines to develop semi-automated DFA tools. The system presented results of feasible assembly sequence in tabular format, roughly similar to manual assembly worksheet (Rong-Kwei

& Cheng-Long, 1992). Satyandra, Das, and Nau (1997) argued that improving the output format can provide design engineers more information for design modifications. Automated machining analysis tools like NEXT-Cut (Tenenbaum & Cutkosky, 1992) warned users if any of the designed features violated predefined constraints. Some of the tools (Yannoulakis, Joshi, & Wysk, 1994; Warnecke & Bassler, 1988) used a scoring strategy to rate manufacturability of design features and offer redesign suggestions, features with lower scores were possible candidates for redesign.

Current state-of-the-art manufacturability analysis tools like DFM Pro (Geometric, 2009), DFM Concurrent Costing (DFMA, 2015), and Cast Designer (Cast Designer, 2015) perform complex analysis on various manufacturing processes and provide feedback to design engineers. These software tools provide manufacturability information at various levels of details and in several modalities. DFMPRO integrates with CAD design tools and provides 3D colored feedback about the design, within the CAD system. Viewers of the feedback need to have DFMPRO installed in their systems. It can also export 2D and text reports to be shared with someone not using DFMPRO. The Boothroyd-Dewhurst DFM tool provides detailed information related to product manufacturability time and cost in tabular format or 2D charts. There are several tools (Madan, Rao, & Kundra, 2007; Lockett, 2005) in research that provide manufacturability feedback in textual format to design engineers.

Many manufacturing companies have their own set of manufacturing guidelines and develop DFM tools tailored to their needs (Satyandra K, Das, & Nau, 1997). Research (Madan, Rao, & Kundra, 2007; Todić, Lukić, Milošević, Jovičić, & J. Vukman, 2012; Wu, Rosen, Wang, & Schaefer, 2015) in building DFM tools is still actively carried on; researchers develop tech-

niques and tools to improve the manufacturability analysis. Two tools were developed under Defense Advanced Research Projects Agency's (DARPA) Adaptive Vehicle Make's (AVM) Instant Foundry, Adaptive through Bits (iFAB) project: CNCRP-ana (Traband, 2013) for machining analysis and CAST-ana (Traband, 2013) for casting analysis. These tools perform multiple types of analysis and provide integrated feedback as portable 3D PDF through 3DIF.

The acceptance and success of the new DFM tools will largely depend on the quality of the feedback they generate. The modality of manufacturability feedback will play a key role in its effectiveness. The next section describes studies in the past that have shown how modality of information is a key component and affects its interpretability and consequently its usefulness.

Visualization and Modality User Studies

The modality of information affects its interpretability, user performance, usability, and workload. Even today, many architecture and manufacturing industries make intensive use of texts and technical 2D engineering drawings (Dori & Tombre, 1995; Yagmur-Kilimci, 2010; Opsahl, 2013). Studies (Tavanti & Lind, 2001; Kashihara, 2009; Yagmur-Kilimci, 2010; Gîrbacia, 2012; Agus, Bettio, Gobbetti, & Pintore, 2007; Ibrahim & Rahimian, 2010; Koramaz & Gülersoy, 2011) have compared differences between 2D and 3D visualization in several domains and the effect it has on human cognition.

Drawings in 2D can lead to alternate 3D interpretations (Butler, 1982). Having variable interpretation of the same drawing can create confusion and hinder in collaboration between functional teams in manufacturing.

Mentally visualizing in 3D with the help of 2D diagrams can be cognitively demanding. Kashihara (2009) compared reaction time and accuracy of mental imaging of 2D and 3D figures.

Results showed that mental imaging of 3D from 2D figures results in high reaction time and low accuracy. It was concluded that the brain frontal lobe and lateral occipital complex which are related for spatial working memory were used more in such tasks. This task also demanded more working memory, thereby, increasing the mental demand needed to perform such tasks.

The previous study described was based off of simple figures; Engineering drawings are more complex. Gîrbacia (2012) compared reaction time and accuracy for creating 3D mental images of complex engineering drawings. Results showed that there was only a small improvement in reaction time and accuracy by using a stereoscopic 3D visualization. The study proposed a new visualization technique called the Augmented Reality Engineering Drawing.

Architects mentally visualize 3D aspects of their design ideas while working with 2D sketches, although architects differ from each other in the ability to visualize in 3D (Yagmur-Kilimci, 2010). 3D visualization of buildings needed domain knowledge and so it is higher in architects compared to non-architects. There was no relationship found between 3D mental visualization task and spatial visualization ability.

The studies mentioned above show how interpretability, performance, usability, and workload is affected by the modality of information. Design engineers experience high cognitive workload when mentally imaging their designs in 3D while working on 2D drawings. They also show that 2D representations can be interpreted in multiple ways and may not always be the best representation of an idea.

Motivation for the Study

In manufacturing when advanced DFM and CAD tools are developed to assist the design engineers in their task, very little attention is paid to the human computer interaction issues related to them (Satyandra K, Das, & Nau, 1997). The modality of information affects understandability and self-explanation of the material (Ainsworth & Loizou, 2003). So, it is important that feedback given to the design engineers should have an appropriate level of information abstraction and should be in an easy to interpret modality.

Visualization effectiveness is typically evaluated based on performance measures such as user response time and accuracy (Huang, Eadesb, & Hong, 2009)t. Although the performance-based measures are helpful in evaluating visualization tools, importance should also be given to user cognitive load, usability, and ease of interpretation. Usability testing and controlled experiments are the bases of evaluation of visualization tools (Chen & Czerwinski, 2000). User performance is largely dependent on the combination of task demands and information needed to perform the task (Sebrechts, Vasilakis, Miller, Cugini, & Laskowski, 1999). The author found limited work on empirical studies conducted on design engineers in manufacturing to evaluate how modality of feedback given to them affects their performance and improves the quality of designs. The 3DIF tool, described in the next chapter, was designed to provide usable feedback visualization to design engineers. It is expected to help them to make their designs more manufacturable in a shorter span of time and with less workload. The motivation of this work is to evaluate the usability and utility of the three-dimensional, integrated feedback provided by 3DIF.

CHAPTER 3. THREE DIMENSIONAL INTEGRATED FEEDBACK TOOL (3DIF)

Motivation

The Three Dimensional Integrated Feedback (3DIF) tool is designed to provide manufacturability feedback to design engineers at the early conceptual design stage. 3DIF is expected to provide design engineers an intuitive and simple way to assess the manufacturability quality of their designs. This will help design engineers to improve the overall manufacturability quality of their designs with fewer and faster design iterations and with greater usability and less cognitive workload. 3DIF tool is a generalizable feedback which can be coupled with different manufacturability analysis such as casting, machining, welding or a combination.

3DIF Process

The underlying platform of 3DIF is Adobe's portable document format or PDF. The manufacturability feedback information is presented in the form of colored data, integrated onto a 3D representation of the part, along with textual information. The colored regions in the 3D data indicate the region of interest. The potential redesign features are highlighted in different colors or by using simple primitive geometries, like spheres or cones. Mapping information to simple representations is expected to be easily comprehensible for design engineers of varying expertise. The use of PDF makes 3DIF inexpensive and highly portable. This will enable teams or clients separated across large distances to share, view and communicate the same information easily. Visualizing 3DIF is independent of any proprietary CAD or DFM tools. Tying the feedback to CAD or DFM tools will force teams or clients to have these tools installed just to visualize the feedback, which can be expensive. The teams receiving 3DIF do not need any expensive tool to

view the feedback. The viewers of 3DIF can use Adobe reader (Adobe Acrobat Reader DC, n.d.), which is free and ubiquitous software (O'Reilly, 2009), to visualize the feedback. 3DIFs have manageable file size and can easily be shared over the web, and viewed across different digital devices like portable hand-held devices. Generating 3DIFs is a fast and automated process. The information to be embedded is passed to the 3DIF generator software tool which embeds the information provided and exports them as a PDF. The data flow from CAD design to 3DIF is shown in Figure 3.

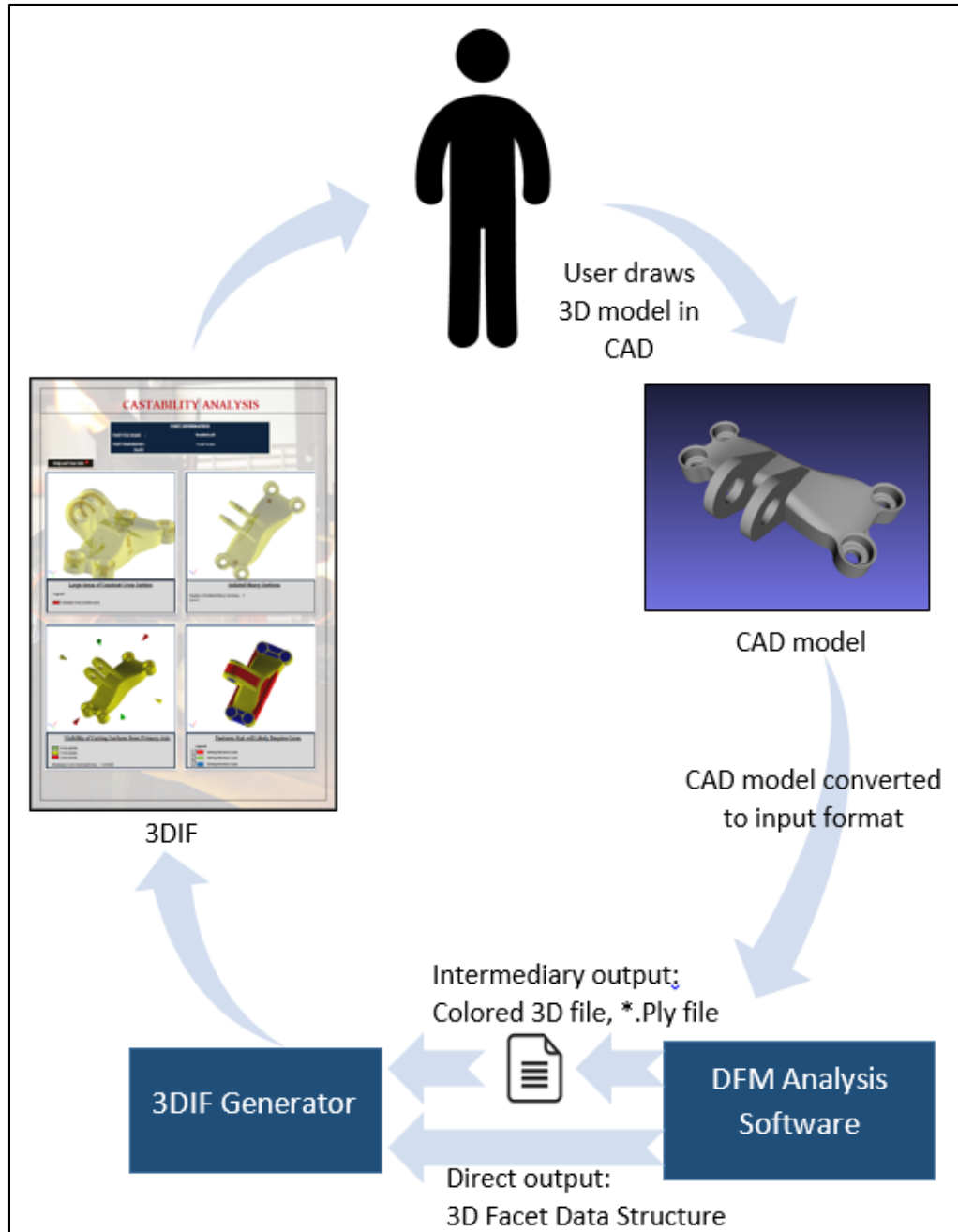


Figure 3: 3DIF integrated into the design process.

The following steps are involved in generating 3DIF from CAD model.

- 1) The design engineer draws a 3D model of a part to be manufactured using a CAD tool.

- 2) The CAD design is fed as an input to a DFM software. The input model should be in a format acceptable by the DFM software, for example, Cast-ana accepts 'stereo-lithography' (*.STL) files, a common 3D file format that has information as a collection of triangles.
- 3) The DFM analysis tools generate manufacturing feedback which is an output in one of two formats, depending on how closely it is coupled with the 3DIF generator.
 - a) If 3DIF generator is used as a standalone tool, the intermediary 3D data produced by the DFM software is written to an external file, typically a Polygon File Format (*.PLY) file, which is then read by the 3DIF generator as an input.
 - b) If 3DIF generator is integrated with DFM software, the DFM tool can pass information directly to 3DIF generator as a raw list of coloured polygons and vertices.
- 4) The 3DIF generator reads the input data, converts it into a native format and embeds the information into a predefined PDF template. This template is published in 3DIF.

3DIF Displays

The 3DIF displays multiple analysis results within a single document, each within its own information window, as illustrated in Figure 4. An information window has two sections for displaying 3D and textual information. Users can perform various levels of operations on 3D data like rotate, pan, zoom, view cross-sectional details about any of the three orthogonal primary axes and change the rendering to transparent and wireframe. Allowing users to interact with the

3D information enables them to diligently explore the data and learn from the feedback information.



Figure 4: Three dimensional Integrated Feedback generated by CAST-ana shows multiple casting analysis results on a part design.

Currently, the tool is integrated with two manufacturing analysis software tools: machining analysis software (CNCRP-ana), and casting analysis software (CAST-ana). These tools take 3D STL designs of a model as input and analyze them against specific manufacturing process rules. The analysis results are exported in the form of 3DIF. CAST-ana uses the 3DIF generator as a standalone software and CNCRP-ana is tightly coupled with the system.

The 3DIF feedback highlights the regions of the CAD design that might be disfavored by a particular manufacturing process, and hence, needs to be redesigned. Isolating the region of interest helps design engineers to focus only on specific features that need a redesign. Generally, a design is checked for various types of problems, feedback related to each of them is embedded in the 3DIF. All the results are grouped together within a single document, each in their own respective information window. Having separate windows for each type of result will help design engineers isolate a single result from the rest. Grouping all these windows in a single document enables them to perceive the results holistically. This allows design engineers to comprehend how different problems are related to one another and to carefully consider the trade-offs between different problems while making design changes.

Figure 4 and Figure 5 show examples of 3DIF generated by the CAST-ana and CNCRP-ana software respectively. In the figures shown, the feedback provides complementary textual information like the model dimension, machining time. The feedback has four information windows each specific to a particular type of analysis. Each window is divided into two sections, a *3D model view section* to display the 3D data and a *metadata section* where other information or controls are provided. The models are colored yellow by default and the regions of interest are highlighted in different colors to make them distinct from the rest of the model. In order to make the hidden surfaces visible, the models are displayed transparently in some of the windows. The

windows have user toolbar built into them. The toolbar provides users with different levels of interaction on the 3D model like changing views, rendering type, panning and rotating.

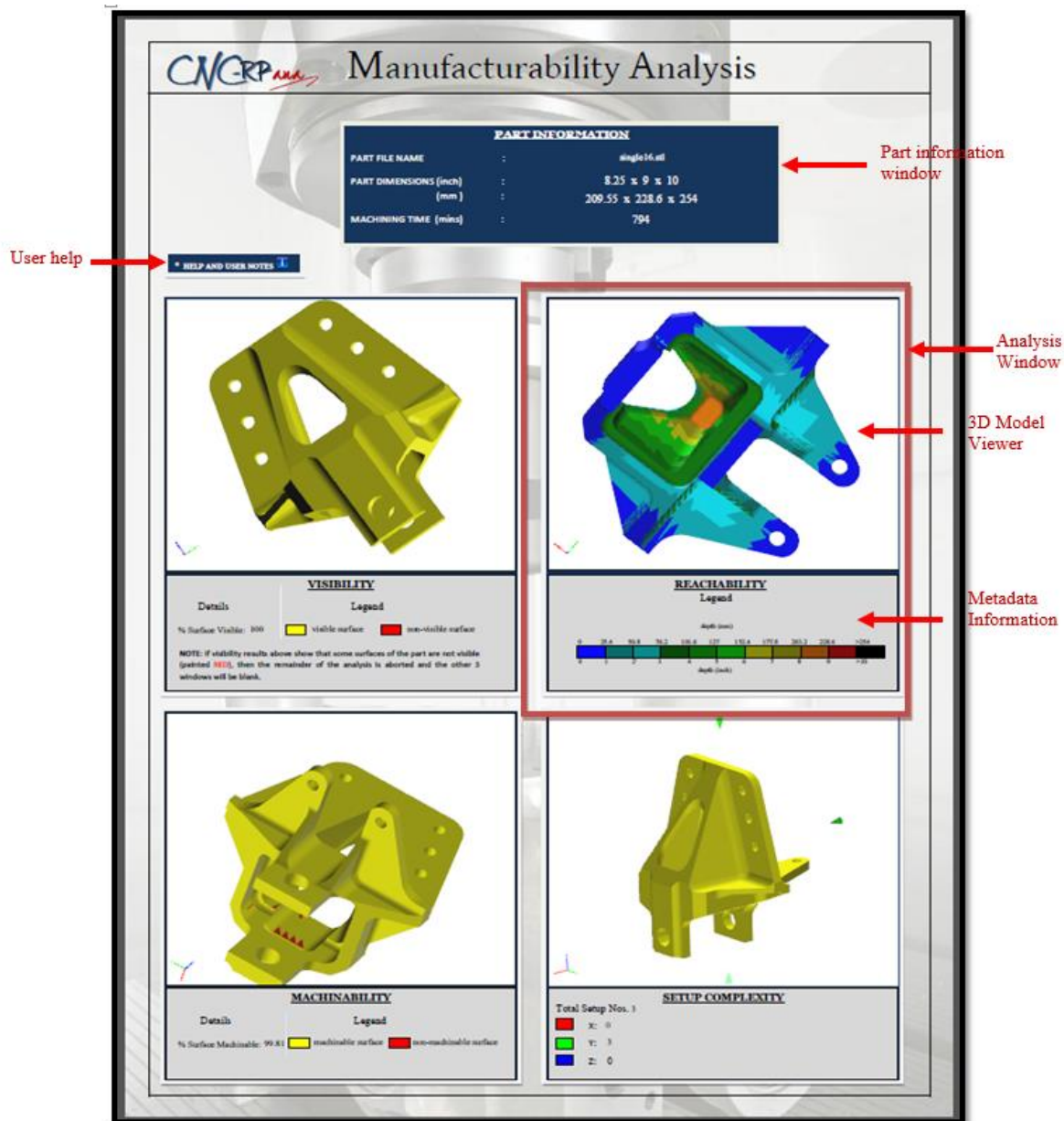


Figure 5: Three dimensional Integrated Feedback generated by CNCRP-ana shows multiple machining analysis results on a part design.

Interpreting 3DIF Manufacturing Feedback Generated by CAST-ana

The CAST-ana software performs four different types of casting analyses. They are

- 1) *Constant cross section analysis*: In casting, constant cross section refers to regions of constant thickness extending over a distance. The analysis result marks areas in the design that forms constant cross sections.
- 2) *Isolated heavy section analysis*: Isolated heavy section refers to regions of cast parts with high volume that require liquid metal feeder to feed molten metal during solidification stage. The analysis result shows the regions that form isolated heavy sections.
- 3) *Visibility analysis*: Visibility analysis finds out the visible surface percentage of the part to help decide a potential parting direction, i.e., the direction in which the part can be cast from.
- 4) *Core area analysis*: Cores are extra supporting material required for features that cannot be made with the help of moulds, e.g. internal cavities, undercuts etc. The analysis points out features that may require cores to be made.

Constant Cross Section Analysis

Constant Cross Sections represent the regions in the part that will suffer from potential metal feeding problems during the casting solidification process. These regions hinder in the process of directional solidification in the casting which results into porosity or cavities in the final casted product. The finished casted component can have defects in them due to uneven cooling. In order to reduce or eliminate constant cross section, the geometry of the model at those regions should either be tapered away from the heavy section or a complete redesign of the feature is needed. In the feedback window, shown in Figure 6, the constant cross-section regions are represented as red solid surfaces placed within the body of the original model. Design engineers can focus on these regions and make necessary changes as needed to reduce them from the final design.



Figure 6: Consistent Cross Section Area Analysis, red solid represents consistent areas.

Isolated Heavy Section Analysis

Isolated Heavy Sections are regions of high volume that require risers or feeders, risers are reservoirs to feed liquid metal to prevent solidification shrinkage. Each isolated heavy section needs a riser set up for it. Risers require complex initial setup and post-machining process to clean up the area of attachment which drives the overall cost of the casting product. A design with less number of isolated heavy sections is preferred. Possible redesign solution may include reducing excess material from these regions, avoiding intersecting features.

In the feedback window, Figure 7, isolated heavy sections are represented as red solid spheres. The location of the spheres gives the location of the actual riser placement. The size of the sphere roughly represents the volume of the risers that will be attached during the casting

process. Design engineers can learn from the feedback about the features in their design that lead to isolated heavy sections and can refine them to reduce the excess isolated heavy sections.

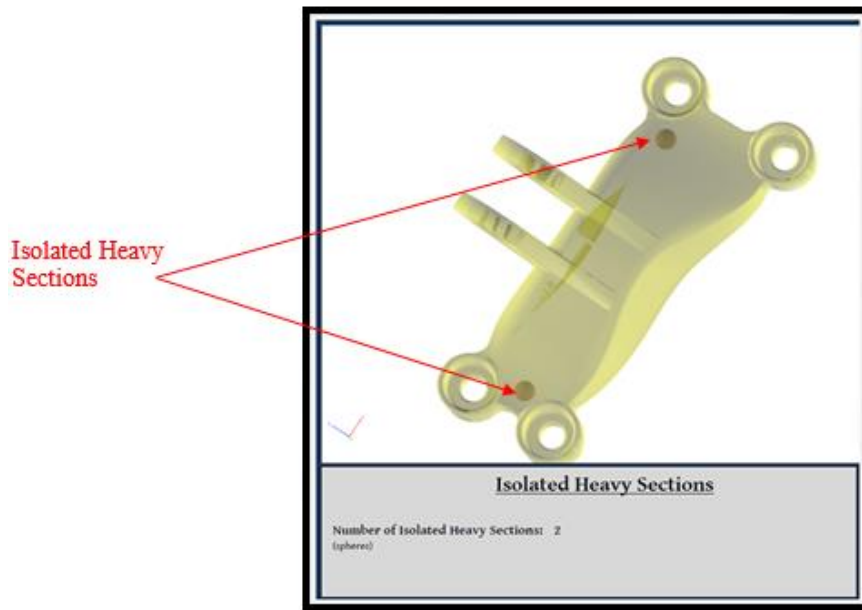


Figure 7: Isolated Heavy Section Analysis, red solid spheres represent riser location.

Core Area Analysis

Cores are extra blocks of materials that are needed to cast some of the features in the design that cannot be produced directly with the mold, for example, creating internal cavities, creating undercuts at an angle to the parting direction etc. Core setup can be a tedious and expensive process which drives the cost of casting.

In the feedback, the cores corresponding to parting direction X, Y and Z axes are represented as red, green and blue solid surfaces respectively, shown in Figure 8. The metadata region of the window provides checkboxes to turn on and off cores, corresponding to a given axis. Figure 9 shows only cores corresponding to Y-axis as parting direction, cores corresponding to X and Z parting directions are turned off. Design that needs fewer cores to be cast is a preferred design. Ways to remove a core can include filling up the internal cavities and removing undercuts.

This may, however, increase the volume of the region and instead could form isolated heavy sections. Design engineers should carefully consider the trade-off while making changes to the design. Visualizing the two feedback together can help design engineers understand the possible interaction between the two types of problems.

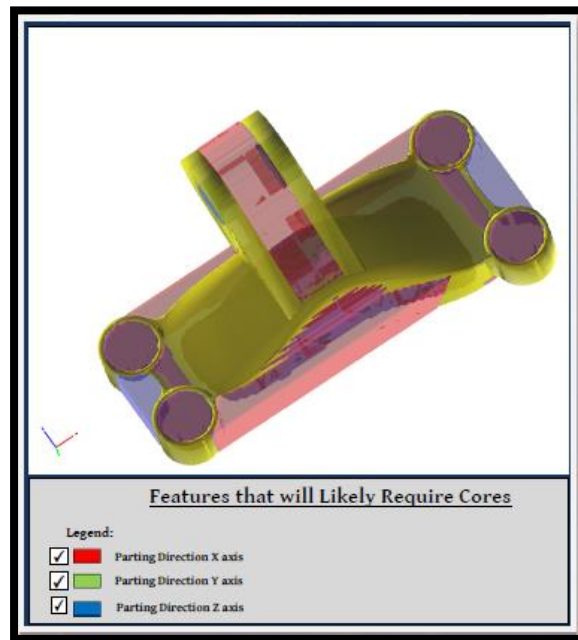


Figure 8: Cores as red, green and blue, with X, Y and Z axes as its corresponding parting direction.

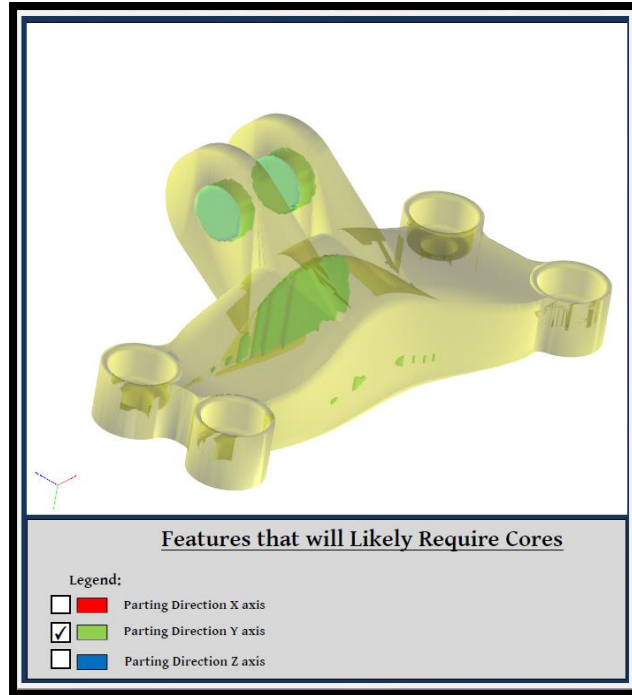


Figure 9: Core as green solid corresponding to Y-axis only.

Visibility Analysis

Visibility Analysis is done to find out the primary axis about which most of the part is visible from 0 and 180 degrees. This helps to select a potential parting direction about which a part can be cast.

In the feedback window, Figure 10, the cones represent angles 0 and 180 about the three primary orthogonal axes, X, Y and Z. The color of the cones represents the relative goodness value of the axes. The green colored cones represent the axis about which the visibility percentage is highest from 0 and 180 degrees. The yellow cones represent axis about which the visibility percentage is average. The red colored cones represent the axis that offer the least visibility about the two angles. The axis with the highest visibility percentage represents a potential parting direction of the design. The red colored surfaces of the model are invisible from 0 and 180 degrees

about all the three primary orthogonal axes. The metadata gives quantifiable information about the visibility percentages.

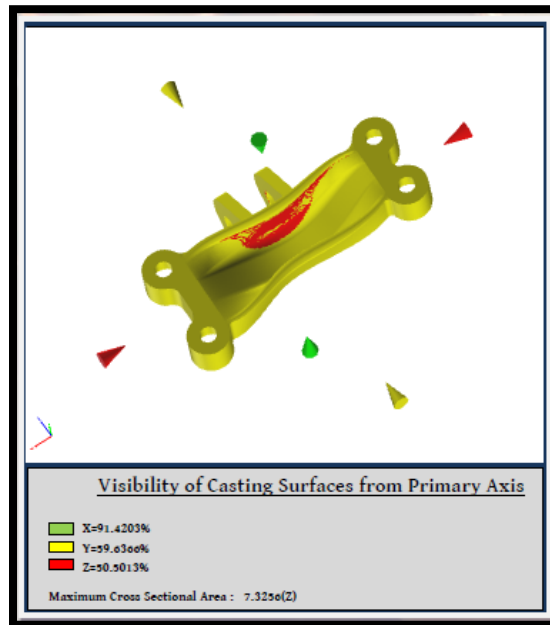


Figure 10: Visibility Analysis, green, yellow and red cones represent relative goodness value of the three axes as parting direction.

Application of Visualization Requirements to the Design of 3DIF

The design of 3DIF can be related to Chittaro's design principles in the following ways:

Mapping: 3DIF maps potential manufacturability problems in the design by coloring the feature or by using primitive geometries like spheres and cones. For example, isolated heavy sections are represented as red spheres, the location of the spheres represents the location of the risers; and the size of the spheres represents the size of the risers needed in those locations.

Selection: 3DIF presents most of the necessary information as colored 3D data. However, supplementary textual information is also provided to assist in decision making. For example, in the visibility analysis, the colored cones are indicative of the relative goodness of the parting directions. Green cones represent maximum visibility and the best candidate for parting direction,

whereas, red cones represent minimum visibility and the least preferred parting direction. Quantitative percentage visibility information is also provided for users to know the absolute values of the percentage visibilities and make decisions about an optimal parting direction to cast the part from.

Presentation: 3DIF presents analysis results in their dedicated information windows. All the information related to an analysis is encapsulated in its window. Each window is independent of the others. 3DIF integrates all these windows in a single document. This enables 3DIF to provide all the feedback in limited space, and easier navigation between the results.

Interactivity: 3DIF presents data in 3D and allows interactions in the form of rotation, zoom in / out, view cross sections and change the surface rendering. These interactions on feedback data are expected to enhance the data exploration capabilities of the users.

Human Factors: Information in 3DIF is provided as simple mapping. This is expected to be comprehensive to design engineers.

Evaluation: This study evaluated the 3DIF tool by conducting a user study with design engineers performing design tasks with it. The study evaluated 3DIF from performance, usability, and cognitive workload perspectives.

CHAPTER 4. METHOD

Research Objective

The goal of this study is to understand how feedback modality affects design performance, usability and workload of design engineers. For this study we have focused on the specific manufacturing process of Casting. The empirical study evaluates performance, usability, and workload of design engineers when they redesign a given part model, to improve its overall casting quality, with the help of different modalities of feedback. The quantitative and qualitative data gathered from the study will help us to better understand design engineers in manufacturing domain, and improve the usability of the prototype 3DIF tool to better assist their needs.

Hypothesis

There are three hypotheses for this study:

- 1) Providing early manufacturability feedback in any modality will help design engineers eliminate more manufacturability imperfections compared to no feedback.
- 2) Manufacturability imperfections introduced in redesign will be independent of feedback modality.
- 3) 3D will help design engineers redesign faster, eliminate more total imperfections, and experience less mental workload compared to the other modalities of feedback.
- 4) 3D feedback will have higher usability compared to other feedback modalities.

Participants

Participants in the research study were engineering students. They had knowledge of casting and design experience in CAD tools. The participants were 18 years old or above and had design experience in casting. A total of 24 subjects, 23 males and 1 female participated in the study. The average age was 22.8 years, range 19 – 28 years. Participants had an average casting experience of 11.42 months, range 0.25 – 42 months.

Independent Variables

Feedback modality is the independent variable in the study. Feedback modality has four levels, *No feedback*, *Textual feedback*, *Two-dimensional (2D) feedback* and *Three-dimensional (3D) feedback*. Information related to casting flaws, (types of flaws, location, area, and volume of the flaw) were provided in all the three feedback types.

- *3D Feedback*: Participants used 3DIF for visualizing feedback in 3D. The original visibility analysis window was removed because it was not needed for this study (see Figure 11).
- *2D Feedback* was replicated from 3DIF tool, however, 3D rotation on the models was disabled (see Figure 12). 2D feedback was a multi-view orthographic projection of the 3D model with six predefined standard views, Top, Front, Left, Right, Back and Bottom View. Participants were able to pan and zoom the model, but not able to rotate the view.
- *Textual Feedback* was formatted as separate tables for every analysis type (see Figure 13.). The location of each non-preferred feature design flaw was given in (x, y, z) Cartesian coordinates. Constant cross section table mentioned the total area of each constant

cross section, in a separate column. Isolated Heavy Section table also provided quantitative data on the volume and attachment area of the risers. Cores corresponding to X, Y and Z axes as parting directions were given in three separate tables.



Figure 11: Customized 3DIF, with no visibility analysis.

CASTABILITY ANALYSIS

Global View
Dropdown
list

New Input
Window
added

Global Views

Top ▾

PART INFORMATION


PART FILE NAME : m1.sld

PART DIMENSIONS : 7.0 x 2.6 x 3.8 (inch)

[Help and User Info](#)



Input Model



Large Areas of Constant Cross Section

Legend:
■ Constant cross section area



Isolated Heavy Sections

Number of Isolated Heavy Sections: 4 (shown)



Features that will Likely Require Cores

Legend:
 Parting Direction X axis
 Parting Direction Y axis
 Parting Direction Z axis

Figure 12: 2D feedback with six predefined views.

Analysis results from CastAna

Part Information	
Name:	m2.stl
Dimension:	7.1 x 2.5 x 4.3
Min X, Min Y, Min Z:	3.51378 x 1.22392 x 2.12398
Max X, Max Y, Max Z:	-3.51378 x -1.22392 x -2.12398

Constant Cross Sections			
X	Y	Z	Area
-3.01	0.59	-3.58	0.225476
2.80	0.63	-2.87	0.174788
-2.26	0.63	-1.11	0.00174788

Isolated Heavy Section				
X	Y	Z	Volume	Attach Area
-0.79	1.46	-2.07	2.00645	1.77804
-3.30	0.63	-2.24	0.574251	0.772189
3.09	0.63	-1.61	0.544862	0.745613

Core Regions with X-Axis as parting direction		
X	Y	Z
-3.18	0.42	-3.45
-2.42	0.04	-2.91
2.68	0.42	-2.74

Core Regions with Y-Axis as parting direction		
X	Y	Z
-0.79	0.59	-1.70
-0.79	0.08	-0.99
-1.96	0.42	-0.78

Core Regions with Z-Axis as parting direction		
X	Y	Z
-3.18	0.42	-3.45
-2.42	0.04	-2.91
2.68	0.42	-2.74
2.22	0.04	-2.24

Figure 13: Textual Feedback.

Dependent Variables

This study measures the dependent variables listed in Table 1.

Table 1: Dependent variables and associated metric.

Variables	Metric	Measurement (Unit)	Frequency	Data Type	
Performance	Cost reduced due to elimination of existing design flaws	Cost	Once each trial	Objective	Continuous
	Cost increment due to introduction of new design flaws	Cost	Once each trial	Objective	Continuous
	Percentage change in overall cost	Percentage	Once each trial	Objective	Continuous
	Redesign time	Minutes	Once each trial	Objective	Continuous
Usability	Comprehensiveness	Point distribution (0 – 100)	Post - experiment	Subjective	Continuous
	Helpfulness	Point distribution (0 – 100)	Post - experiment	Subjective	Continuous
	Ease of navigation	Point distribution (0 – 100)	Post - experiment	Subjective	Continuous
	Confidence	Likert Scale 1-5	Once each trial	Subjective	Ordinal
Workload	Mental Demand	NASA-TLX 0 - 10	Once each trial	Subjective	Ordinal
	Physical Demand	NASA-TLX 0 - 10	Once each trial	Subjective	Ordinal
	Temporal Demand	NASA-TLX 0 - 10	Once each trial	Subjective	Ordinal
	Performance	NASA-TLX 0 - 10	Once each trial	Subjective	Ordinal
	Effort	NASA-TLX 0 - 10	Once each trial	Subjective	Ordinal
	Frustration	NASA-TLX 0 - 10	Once each trial	Subjective	Ordinal

Performance

Cost reduced due to elimination of existing flaws

The cost of the final design depends on how many existing flaws were eliminated or reduced in cost. This dependent variable captures the improvement of the design quality by the reduction of cost of the part due to elimination or reduction of existing design flaws. A cost model is shown in Table 2. Cost is associated with constant cross sections, isolated heavy sections, cores, and weight change of the part.

Table 2: Cost model used in the study.

Features	Factors	Cost (units)
Consistent Cross Section	Total Area	Change in area in $\text{inch}^2 * 300$
Isolated Heavy Section	Number Area of attachment	Change in number * 1000 Change in area in $\text{inch}^2 * 300$
Cores	Number	Change in number * 1000
Overall weight	Weight	If weight change is greater than 10%, Change in weight in pound * 500.

Cost increment due to introduction of new flaws

The redesign process can introduce new design flaws and increase the overall cost. This dependent variable is expected to be independent of the feedback modality and related to the design expertise of the design engineers.

Percentage change in overall cost

Participants redesign a given model with the goal to improve its overall final cost. Percentage change in cost is a cumulative measure of cost increased due to introduction of new flaws and cost reduction due to elimination of existing design flaws.

Time taken to redesign

The dependent variable measures the time taken, in minutes, to redesign a part model. It is expected that both expertise of participants and modality of feedback will affect the total redesign time.

Usability

Comprehensiveness of feedback

Comprehensiveness is the measure of ease of interpretability of feedback information. It is measured by asking the participant to distribute 100 points between the three modalities of feedback.

Helpfulness of feedback

Helpfulness is measured by asking the participant to distribute 100 points between the three feedback modalities. Helpfulness determines how helpful each modality of feedback was to improve the cost of the final design.

Ease of Navigation

Ease of navigation measures the ease with which the participants were able to browse between different data and gather the required information. It is measured by asking the participant to distribute 100 points between the three feedback modalities.

Confidence in final design

Confidence is measured using Likert scale response. It is the measure of how confident participants were about the quality of their final design. This measure captures a participant's own assessment of how well they believe they have addressed the manufacturing issues from the feedback.

Workload

Workload

Workload is measured via the NASA Task Load Index (Hart & Staveland, 1988). There are six subscales, each rated from 0-10: mental demand, physical demand, temporal demand, performance, effort and frustration.

Experimental Task

In the design task, participants were given an input CAD model. The CAD model had casting design flaws introduced in them. Depending on the trial, participants were either provided feedback in one of the three modalities or no feedback. Participants were asked to interpret the feedback and redesign the original model with the goal of reducing the original design flaws. Participants were asked to follow the design constraints shown in Table 3.

Table 3: Design constraints.

CONSTRAINTS	DESCRIPTION
Weight constraint	Their designs had to be within 10% of the initial weight of the part, i.e. they were not allowed to add or remove material that would alter the weight of the part significantly.
Bounding envelope constraint	The final design had to lie within a reference 3D model. This constraint was intended to maintain the topology of the original part given to them.
Stress constraint	Their designs had to meet the given stress constraint.

They were not allowed to use any external analysis tool to verify that the design was within constraints, but must rely on their expertise.

Experimental Design

The experiment is a 1 x 4 (*Feedback Modality*) within subject design experiment. Subjects performed tasks in all of the four of feedback modalities.

To avoid the complexity of the designs affecting the final results, the complexity of the part models was kept uniform across all the four trials. Figure 14 shows the isometric view of the four models used in the study.

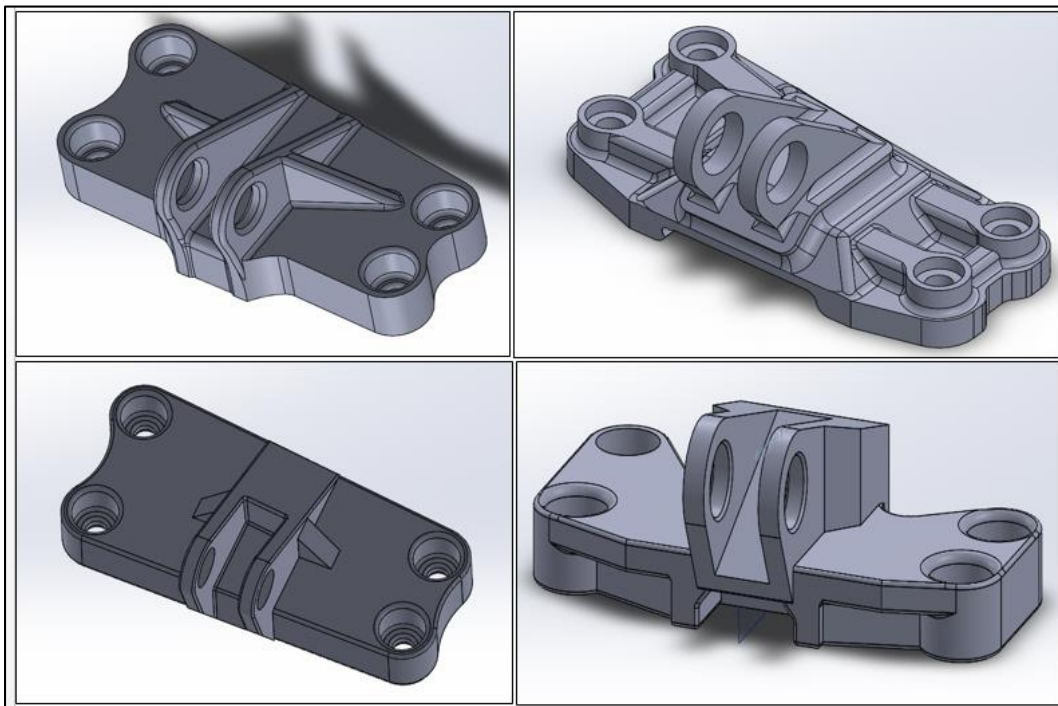


Figure 14: Isometric views of the four models used in the study for the trials. The sequence of the models was randomized.

Controlled design flaws were introduced in the original designs to control the overall complexity and imperfections. The complexity of the model was based on the types of features and the complexity of redesign needed to eliminate those features. In terms of visual difficulty, each of the designs had two types of flawed features. Features those were clearly visible to the

naked eye like sharp undercuts, areas of high volume. The second type of features were subtle, like very small negative drafts, and internal cavities.

To reduce any learning effect of the participants on the final result, the sequence of the input model and feedback modality was randomized for every participant. The counter-balance table (4 by 4 Latin square) for the first four participants is shown below in Table 4.

Table 4: Counter-balance table to minimize learning effect in participants across trial, first four participants shown.

	P1	P2	P3	P4
Trial1	Model1, None	Model2, Text	Model3, 2D	Model4, 3D
Trial2	Model3, Text	Model4, None	Model1, 3D	Model2, 2D
Trial3	Model4, 2D	Model3, 3D	Model2, None	Model1, Text
Trial4	Model2, 3D	Model1, 2D	Model4, Text	Model3, None

Testing Environment

Participants worked on a PC / Laptop running CAD software of their choice (Solidworks (Solidworks, n.d.), PTC Creo (PTC Creo, n.d.), SolidEdge (Solidedge, n.d.)) and Adobe reader to render the pdf feedback files. Remote participants needed TeamViewer (TeamViewer, n.d.) software for remote screen sharing, file transfers and VOIP calls. The study used CAST-ana software to generate casting feedback of the designs in Text, 2D and 3D.

Procedure

After the consent form was signed, participants filled out a preliminary questionnaire and underwent a training session. They were trained on the following

- i) The Casting non-preferred features they were given feedback on.
- ii) The CAD features to use in the study, in the design task.

- iii) The three feedback types, Textual, 2D and 3D feedback
- iv) Cost model, shown in Table 2, used to rate the quality of the designs.
- v) NASA-TLX workload survey.
- vi) A training design trial.

The training session concluded with a training questionnaire. Once participants were properly trained they conducted four trials of the design task. Each of these trials had a post-trial questionnaire and a workload survey at the end of the trial. After the completion of all the trials, they were asked to fill out a post-experiment questionnaire followed by debriefing about the prototype 3DIF tool.

CHAPTER 5. RESULTS

Data Analysis

A four by one ANOVA was performed on the data to find if the mean of the groups differed significantly. Post-hoc Tukey's HSD test was performed on the four groups to find individual significance between each pair. Cohen's d-test was also performed to calculate the effect size. For ANOVA analysis, the effect is considered highly significant for p-values less than 0.001, significant for p-value less than .05 and marginally significant for p-value less than .10, otherwise, the effect is non-significant. The Cohen's d effect size between 0.2 and 0.5 is considered small, between 0.5 and 0.8 as medium, and greater than 0.8 is considered as large. The bar graphs shown below have alphabet color coding (A, B, C) associated with each feedback modality group. The alphabets represent the groups that are significantly different from each other, i.e., a group with coding A is different from B and C. It also represents the groups that are significantly better than the other. For example, A is significantly better than B and C, B is significantly better than C. ANOVA analysis showed that the trial order had no significant effect on any of the dependent variables.

Performance

Cost reduced due to elimination of existing flaws

The dependent variable (DV) measures the quantitative value of cost improvement of the initial design due to the elimination of existing design flaws. Feedback modality was highly significant in terms of cost reduction due to the elimination of existing flaws ($F(3, 92) = 10.25, p < .0001$). Participants were able to eliminate more numbers of existing flaws when feedback was

given in visual modality compared to textual and no-feedback. Figure 15 shows the bar graph between the feedback modality and the existing cost reduced. Tukey's HSD post hoc comparisons indicated that the mean score of 3D ($M = 5,904$, $SD = 3,210$) and 2D ($M = 5,033$, $SD = 2,516$) was significantly higher than textual ($M = 3,067$, $SD = 1,953$) and no-feedback ($M = 2,547$, $SD = 1,805$). There was, however, no significant difference between 2D and 3D feedback, likewise, textual and no-feedback was not significantly different.

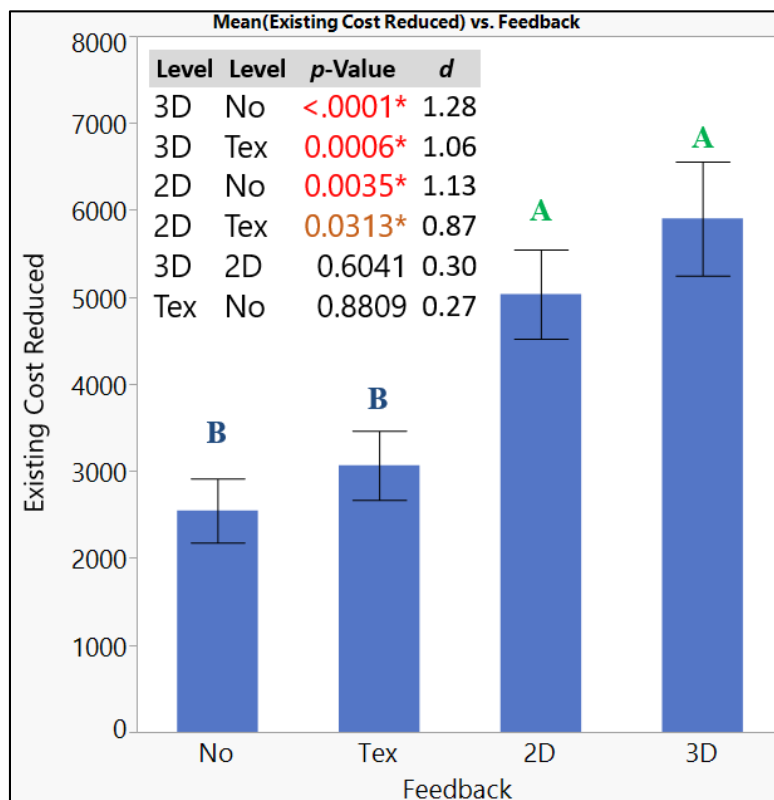


Figure 15: Mean (Existing Cost Reduced) and Feedback modality. The standard errors are shown.

Cost increment due to introduction of new flaws

The design task also resulted into the introduction of new flaws into the original design which led to the increment of overall initial cost. The dependent variable quantitatively measures the amount of new cost introduced due to the introduction of new flaws.

The results show that feedback modality had no significant effect on the amount of new cost introduced. The effect size reported between the modalities was also small. Figure 16 shows the graph between the mean of new cost introduced and the feedback modality. The standard errors are also shown.

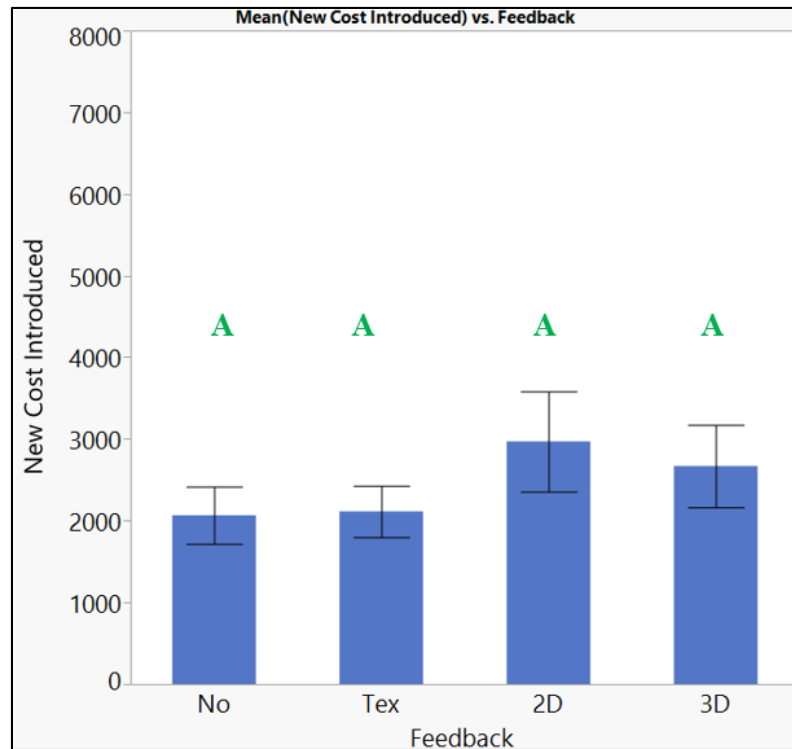


Figure 16: Mean (New Cost Introduced) vs. Feedback. The standard errors are shown.

Overall percentage change in cost

The overall cost is a cumulative measure of both the existing cost reduced and the new cost introduced. Figure 17 shows the graph between percentage change in cost and the feedback modality. The results show that feedback modality was highly significant in terms of the overall cost improvement of the original design ($F(3, 92) = 7.8, p = .0001$). Tukey's HSD post hoc comparisons indicated that the mean score of 3D ($M = -23.8, SD = 16.0$) was significantly higher than textual ($M = -6.7, SD = 15.1$) and no-feedback ($M = -3.2, SD = 16.3$). The effect

size between them was also large with $d = 1.08$ and $d = 1.25$ respectively. There was no significant difference between 3D and 2D ($M = -15.27$, $SD = 16.5$) and the effect size was also small $d = 0.41$. 2D and no feedback was significantly different but showed a medium effect size of $d = 0.59$. Textual feedback was not significantly different than 2D and no feedback, they also had a small effect size. Textual feedback was not significantly different from no-feedback and the effect size between them was small with $d = 0.22$.

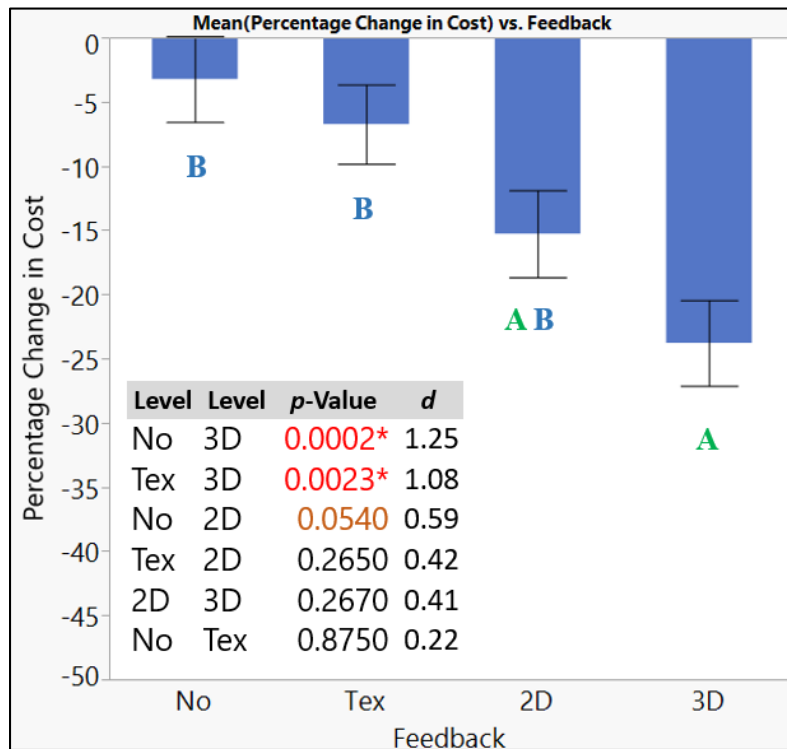


Figure 17: Mean (Percentage Change in Cost) vs. Feedback. The standard errors are shown.

Redesign Time

The time was measured in minutes. Participants had a maximum allowable time of 20 minutes per trial. The effect of feedback modality on redesign time was inconclusive because several participants exceeded the 20 minutes allotted time limit and were stopped. None of the

differences were statistically significant. Figure 18 shows the graph between the redesign time and the feedback modality.

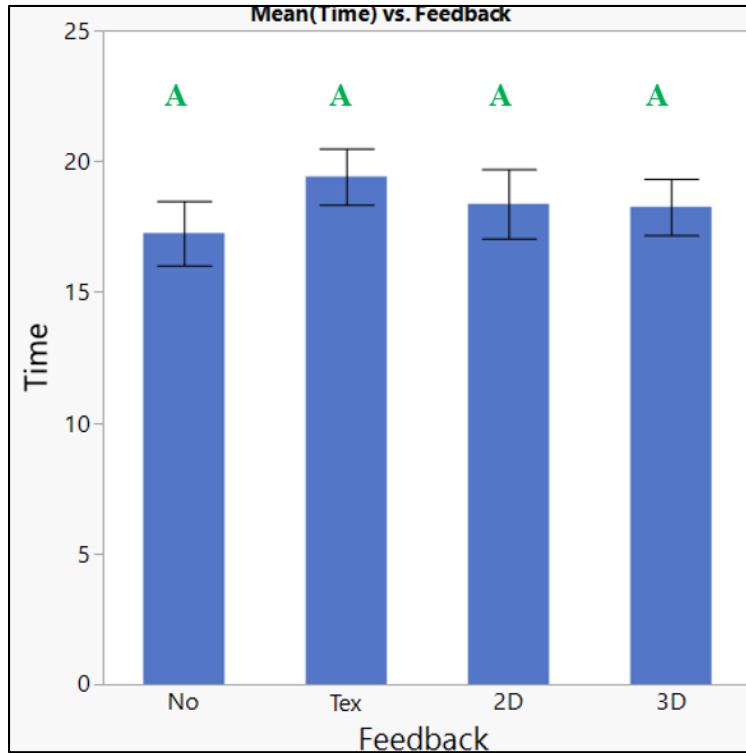


Figure 18: Mean (Time) vs. Feedback. The standard errors are shown.

Usability

Comprehensiveness

The comprehensiveness is the measure of ease of interpretability of information. The modality of feedback was highly significant on the subjective comprehensiveness of the participants ($F(2, 69) = 69.33, p < 0.001$). Tukey's HSD post hoc comparisons indicated that the mean score of 3D ($M = 57.2, SD = 15.0$) was significantly higher compared to both 2D ($M = 29.00, SD = 12.40$) and textual ($M = 13.37, SD = 11.71$). The comprehensibility of 2D feedback was significantly higher than textual feedback. The effect sizes between the modalities were very large as shown in the graph.

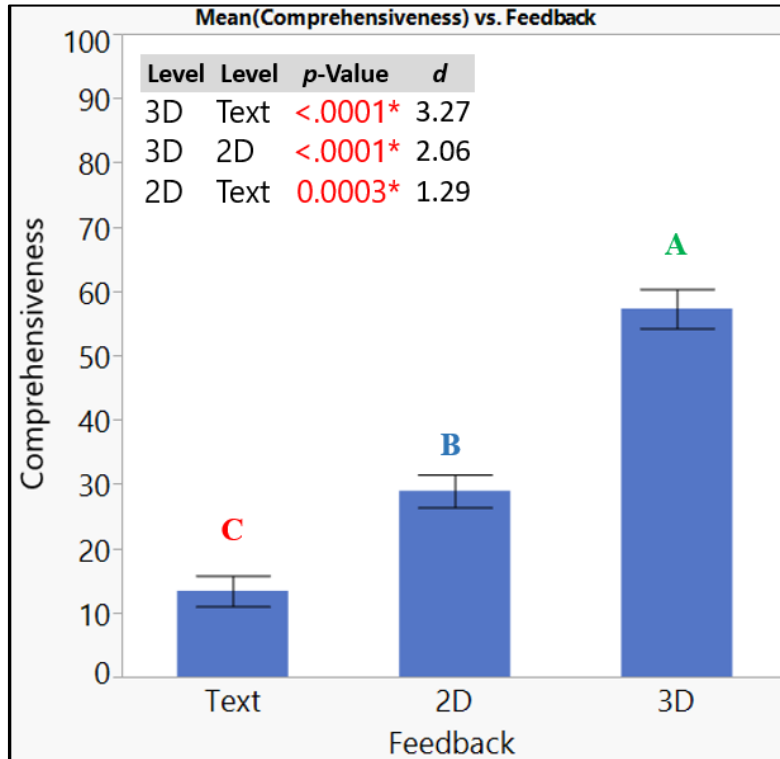


Figure 19: Mean (Comprehensiveness) vs. Feedback. The standard errors are shown.

Helpfulness

Helpfulness is the measure of the usefulness of feedback to remove the existing flaws in the original design. The results show that modality of feedback was highly significant on the subjective helpfulness of the participants ($F(2, 69) = 89.15, p < 0.001$). Tukey's HSD post hoc comparisons indicated that the mean score of 3D ($M = 57.20, SD = 13.89$) was significantly higher compared to both 2D ($M = 31.29, SD = 12.14$) and textual ($M = 11.25, SD = 9.39$). The helpfulness of 2D feedback was significantly higher than textual feedback. The effect sizes between the modalities were very large as shown in the graph.

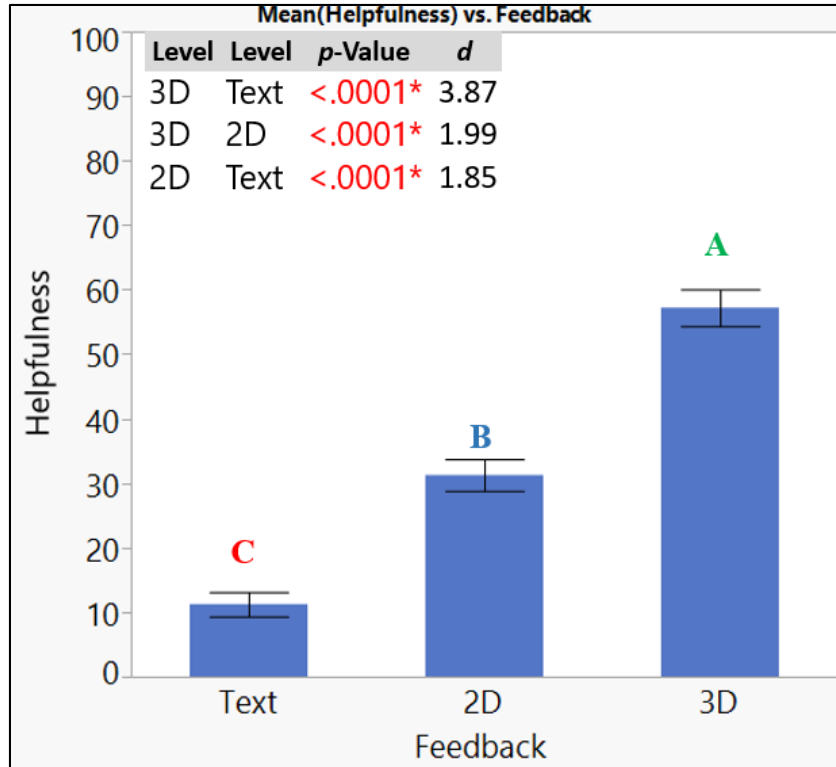


Figure 20: Mean (Helpfulness) vs. Feedback. The standard errors are shown.

Ease of Navigation

The ease of navigation is the measure of the ease of browsing the different information. The results show that modality of feedback was highly significant on the subjective ease of navigation rating of the participants ($F(2, 69) = 54.60, p < 0.001$). Tukey's HSD post hoc comparisons indicated that the mean score of 3D ($M = 61.29, SD = 21.66$) was significantly very high compared to both 2D ($M = 25.58, SD = 13.81$) and textual ($M = 13.04, SD = 12.89$). The ease of navigation of 2D feedback was significantly higher than textual feedback. The effect sizes between the modalities were very large as shown in the graph.

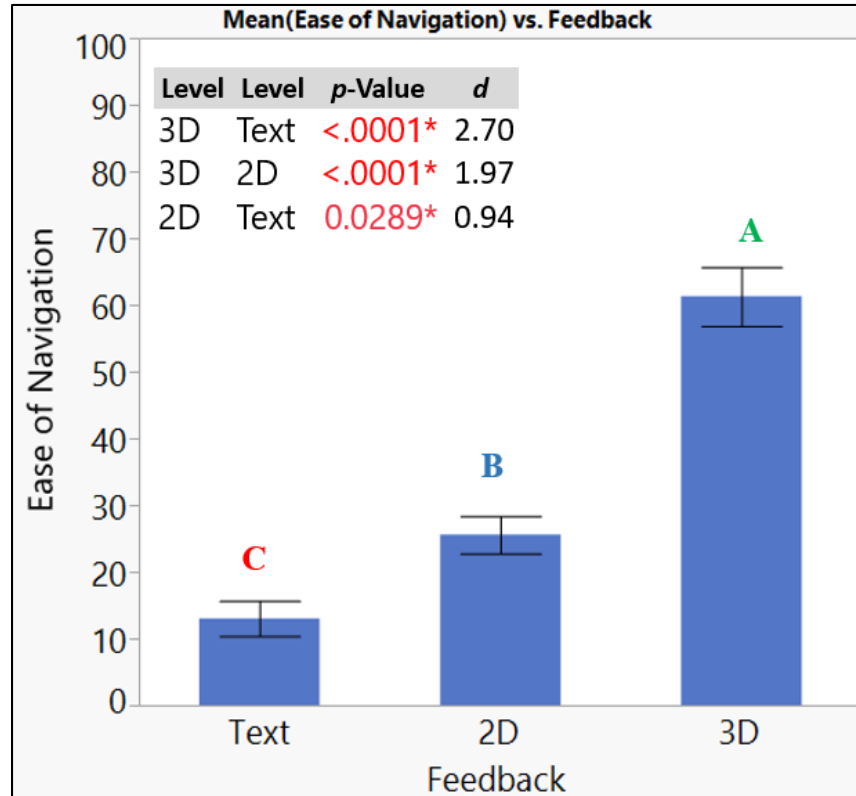


Figure 21: Mean (Ease of Navigation) vs. Feedback. The standard errors are shown.

Confidence

The dependent variable is the measure of the confidence level of the participants with respect to the final casting quality of their redesigned part models. The results show that feedback modality had high significance on participants' confidence level ($F(3, 92) = 7.11, p = 0.0002$). Tukey's HSD post hoc comparisons indicated that the mean score of 3D ($M = 2.80, SD = 1.00$) was significantly higher than textual ($M = 1.83, SD = 1.00$) and no-feedback ($M = 1.62, SD = 0.87$). The 2D feedback ($M = 2.41, SD = 1.06$) was significantly higher than no feedback. There was, however, no significant difference between 2D and 3D feedback, and textual and no-feedback modalities. The effect size reported between these pair of modalities was also very small as shown in the graph,

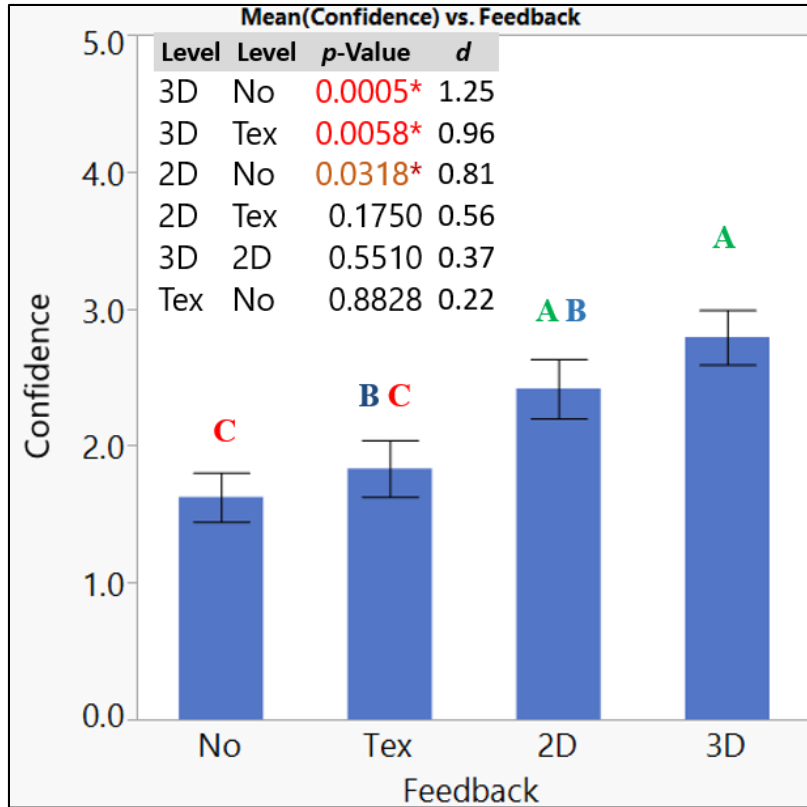


Figure 22: Mean (Confidence) and Feedback modality. The standard errors are shown.

Workload

Mental

The design tasks were mentally taxing. This dependent variable is the measure of participants' subjective rating of how mentally demanding the task was. The results show that modality of feedback had a very high significance on participants' mental demand during the tasks ($F(3, 92) = 9.39, p < 0.0001$). Tukey's HSD post hoc comparisons indicated that the mean score of textual ($M = 6.37, SD = 1.93$) and no-feedback ($M = 6.12, SD = 1.86$) was significantly high compared to 2D ($M = 4.52, SD = 1.93$) and 3D-feedback ($M = 4.12, SD = 1.92$). There was, however, no significant difference between 2D and 3D feedback, and text and no-feedback. The effect size reported between these pair of modalities was also very small as shown in the graph,

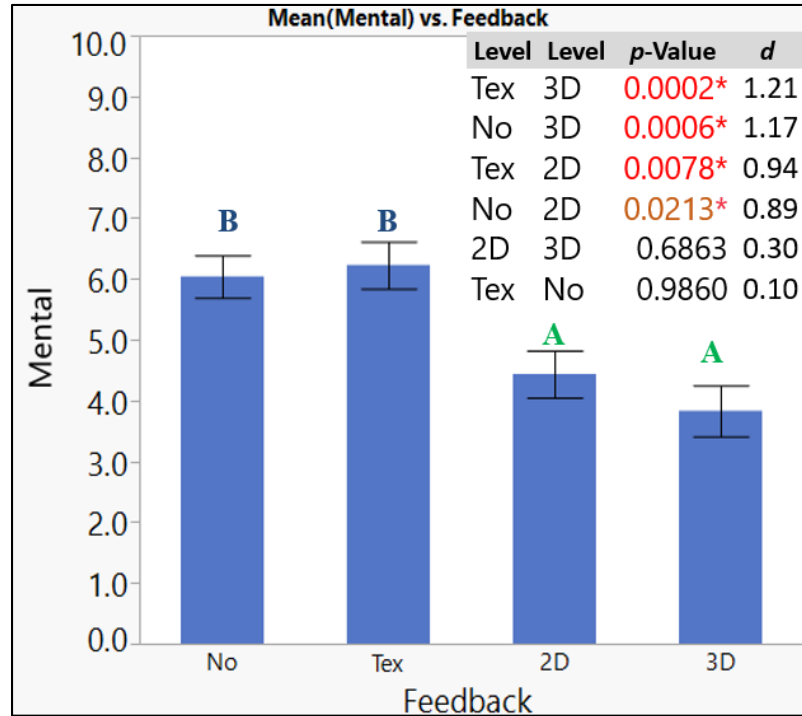


Figure 23: Mean (Mental workload) and Feedback modality. The standard errors are shown.

Physical

The design tasks were not physically intensive. This dependent variable measured participants' subjective rating of how physically demanding the task was. The results show that the physical demand was very low and was not significantly affected by the feedback modalities

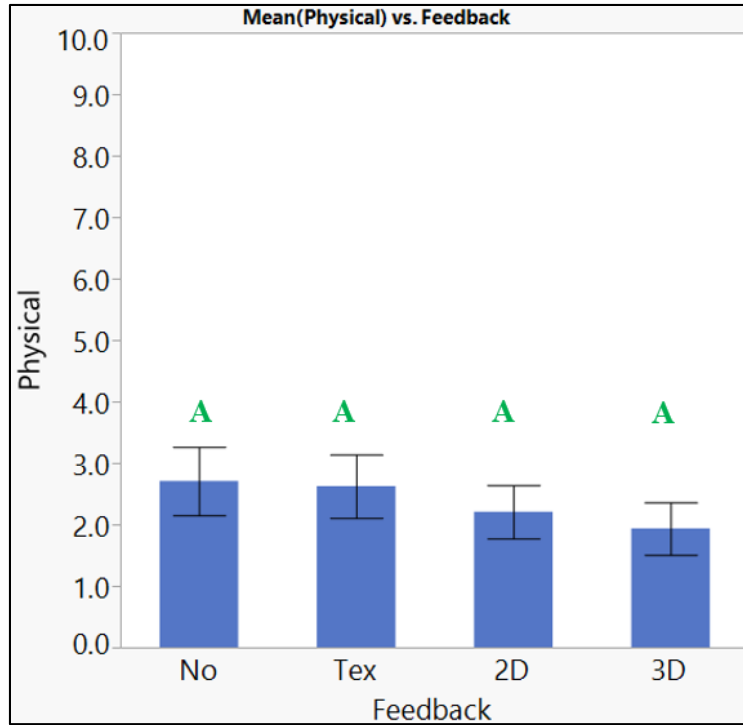


Figure 24: Mean (Physical demand) and Feedback modality. The standard errors are shown.

Temporal

Temporal demand measures participants' subjective rating of how time pressured the participants were during the task. The result show that temporal workload was very low during the task and feedback modality had no significant effect on participant's temporal workload.

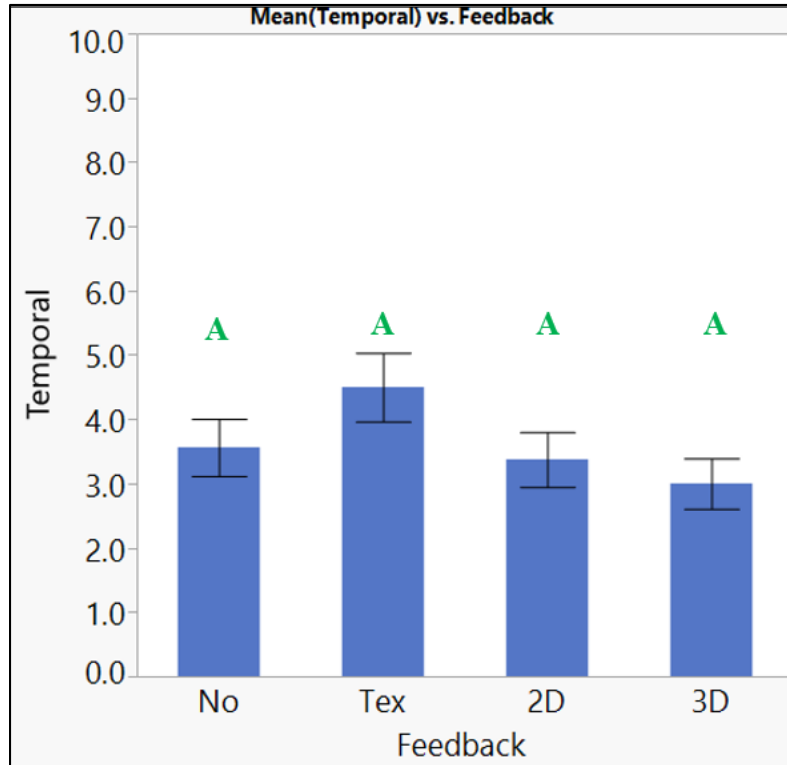


Figure 25: Mean (Temporal) and Feedback modality. The standard errors are shown.

Performance

Performance measures participants' subjective rating of how successful they were in accomplishing the task. The results show that feedback modality was highly significant on participants' performance ($F(3, 92) = 3.90, p = 0.01$). Tukey's HSD post hoc comparisons indicated that the mean score of 3D feedback ($M = 6.56, SD = 1.92$) was significantly high compared to no feedback ($M = 4.68, SD = 1.82$). 2D ($M = 6.10, SD = 2.15$) was marginally significant compared to no-feedback. The effect size between 3D and no-feedback was large with $d = 1.00$, whereas, the effect size between 3D and textual ($M = 5.29, SD = 2.33$) was medium with $d = 0.60$ respectively. The mean of 3D was not significantly different than the 2D and the effect size was small with $d = 0.22$.

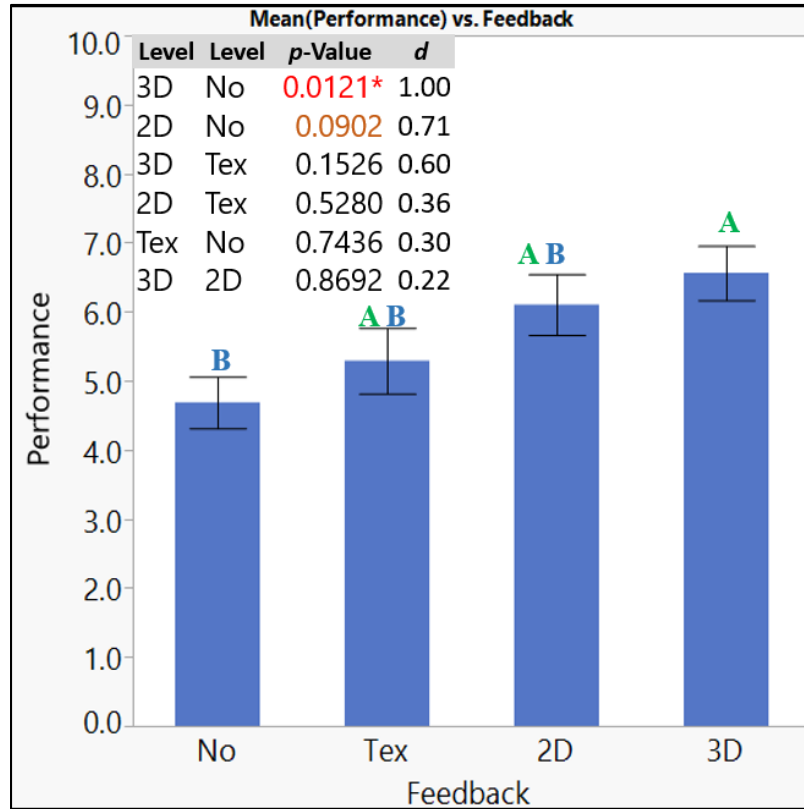


Figure 26: Mean (Performance) and Feedback modality. The standard errors are shown.

Effort

Effort is the subjective measure of how hard participants had to work to complete the task. The results show that feedback modality had significance on participants' efforts required to complete the task ($F(3, 92) = 4.6, p = 0.0047$). Tukey's HSD post hoc comparisons indicated that the mean score of 3D feedback ($M = 3.92, SD = 2.29$) was significantly low compared to textual feedback ($M = 6.30, SD = 2.28$). Although, there was no significant difference between the means of textual and 2D modality, they had a medium effect size of $d = 0.57$. The means of 2D and 3D modality were not significantly different and also had a small effect size of $d = 0.43$.

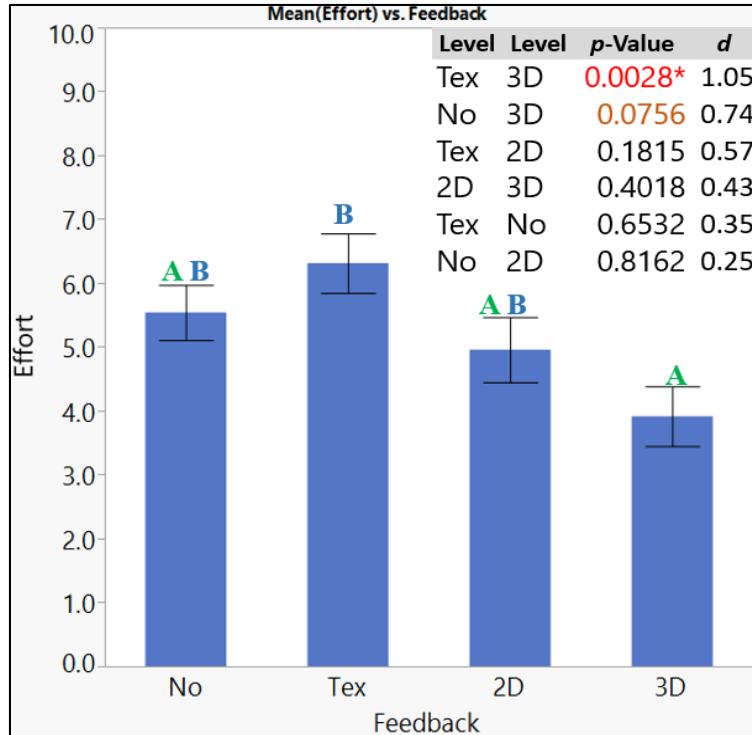


Figure 27: Mean (Effort) and Feedback modality. The standard errors are shown.

Frustration

Frustration is the measure of how insecure, discouraged, irritated, stressed and annoyed the participants were during the task. The results show the feedback modality had very high significance on the frustration of the participants ($F(3, 92) = 7.19$, $p = 0.0002$). Tukey's HSD post hoc comparisons indicated that the mean score of textual feedback ($M = 5.41$, $SD = 2.21$) was significantly high compared to 2D ($M = 3.47$, $SD = 2.18$) and 3D ($M = 2.58$, $SD = 1.98$). The mean of 3D feedback was significantly low compared to no-feedback ($M = 4.37$, $SD = 2.45$). There was no significant difference between the means of 2D and 3D, and no and textual feedback.

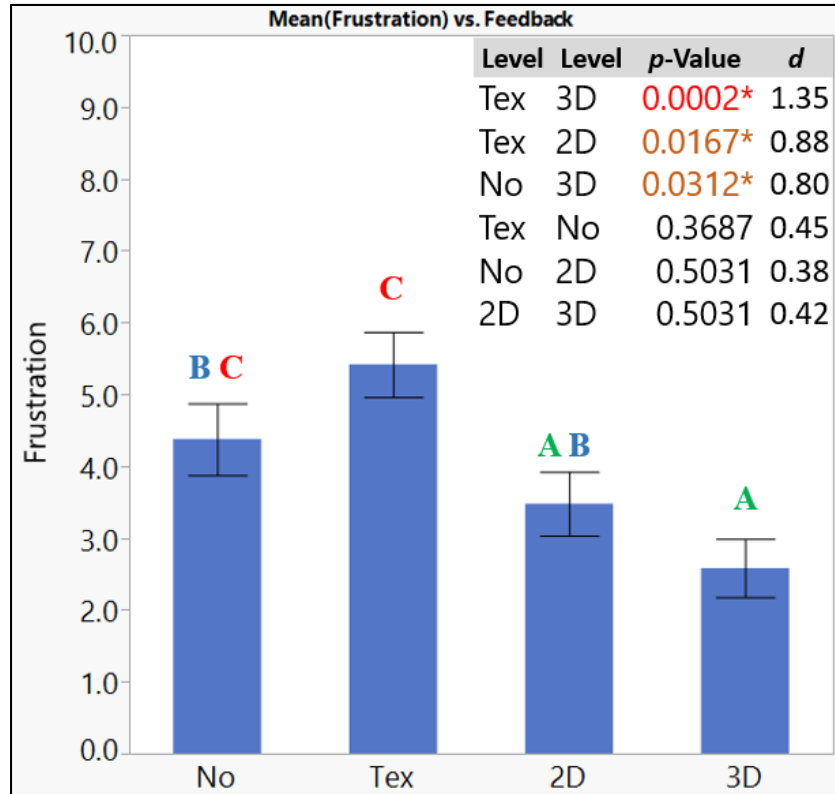


Figure 28: Mean (Frustration) and Feedback modality. The standard errors are shown.

Result Summary

The trial order did not have a significant effect on any of the dependent variables. Table 5 below shows the entire summary of the effect of the feedback modality on the dependent variables.

Table 5: The result summary of the effect of feedback modality.

Variables	Metric	No	Text	2D	3D
Performance	Existing cost reduced	B	B	A	A
	New cost introduced	A	A	A	A
	Percentage change in overall cost	B	A B	A	A
	Redesign time	A	A	A	A
Usability	Comprehensiveness	-	C	B	A
	Helpfulness	-	C	B	A
	Ease of Navigation	-	C	B	A
	Confidence	C	B C	A B	A

Workload	Mental Demand	B	B	A	A
	Physical Demand	A	A	A	A
	Temporal Demand	A	A	A	A
	Performance	B	A B	A B	A
	Effort	A B	B	A B	A
	Frustration	B C	C	A B	A

CHAPTER 6. DISCUSSION AND CONCLUSION

The first hypothesis was that manufacturability feedback in any modality will help design engineers to eliminate more existing design flaws compared to no feedback. The results partially confirm the above hypothesis. We expected to see less of a reduction in cost due to existing design flaws when participants were not provided any feedback. The results show that cost reduction, when participants were not given any feedback, was significantly lower when compared to the cost reduction when participants were provided feedback in either 2D or 3D modality. This behavior supports the first hypothesis. However, results show that there was no significant difference between textual and no-feedback scenarios. This behavior contradicts our first hypothesis. The textual feedback caused extra workload to interpret when compared to the other feedback modalities, so given the finite redesign time, the feedback was not as helpful in redesigning the part, when compared to the no-feedback condition. Allowing more time per trial may have resulted in to performance difference between textual and no-feedback. It is expected that there may be higher performance improvement with textual modality compared to no-feedback.

The second hypothesis stated that cost increased due to the introduction of new design flaws will be independent of feedback modality. This hypothesis is fully supported. The feedback modality was only expected to help participants eliminate the existing flaws in the design. It did not provide guidance on how to address the design flaws identified, and so was not expected to have any effect on participants' design skills in terms of introducing new design flaws. The feedback gave information about the location of the flaws, it did not give participants any redesign suggestion on how to eliminate those flaws. The redesign decisions were made by the participants which were dependent on their expertise as a design engineer. The results support that the feedback modality had no significant effect on the new cost introduced by the participants. It

is possible that learning about manufacturability will take place after a design engineer uses the feedback many times. This learning effect could mitigate the tendency to introduce new flaws while fixing existing flaws. If the design task is performed iteratively, participants using the 2D or 3D modality feedback will be able to learn quicker compared to textual and no-feedback. Design engineers may introduce lesser number of flaws in every subsequent design iteration and converge to a better design faster. This would be an area of future work.

The third hypothesis stated that 3D will result in fastest redesign time, eliminate more total imperfections with less mental workload compared to the other modalities of feedback, the results partially support this. The results show that participants eliminated significantly higher existing flaws in 3D modality compared to textual and no-feedback. The mental workload associated with the 3D feedback was also significantly lower compared to textual and no feedback. However, 3D was also expected to be significantly different than 2D. The results do not confirm this. The 3D modality was not significantly different than 2D both in terms of existing flaw reduction and mental workload. The performance difference between 2D and 3D could have been significant if models of higher complexity were used for the design task. Participants were given models of medium complexity in all the trials, they may have located the flaws easily from both 2D and 3D feedback. There was also no difference in mental workload because most of the workload came from the design task itself as opposed to workload from interpreting the feedback. A very complex model may be difficult to interpret with 2D compared to 3D which can result into workload difference.

The fourth hypothesis stated that 3D modality will have higher usability compared to the other modalities. The results completely support the hypothesis. The participants rated 3D feedback as more usable compared to other modalities. The differences between 2D and 3D were

subtle: they were completely the same except for the ability to rotate the 3D feedback to any orientation desired by the participant. While 3D feedback was an improvement over 2D, the differences were not significant. Many of the advantages of 3D over 2D were more in the usability area, as discussed below.

The results of the study show that modality affects interpretability, workload and performance of its users in casting design. As stated by Sackett et al. (2007), while presenting data to the users it is highly critical to understand the users' tasks and requirements, and how the information will be used by them to solve the given problem. Although, information about the casting flaws, example position information, volume and area, were provided in all the three types of feedback yet the performance of the participants in textual format was no better than providing them with no feedback. In fact, providing textual feedback had an adverse effect on the design task. It resulted in more frustration, required more effort to accomplish the task.

The usability results show that participants favored the use of 3D feedback over both 2D and textual. The textual feedback was the least favored modality. This is likely to be attributed to some of the Chittaro's, 2006 visualization design principles. Textual feedback lacked appropriate mapping of information and interactivity. In text, all the necessary information was mapped to numerical digits, for example, the spatial location of casting design flaws and their attributes like area and volume were represented as numbers. In 2D and 3D, the same information was mapped to simple 3D geometry like spheres to represent both location and volume of isolated heavy sections, or colored faces in the model to show both the location and the total area of constant cross sections.

The 2D and 3D feedback were completely identical except for a higher level of interactivity in 3D compared to 2D. The interactivity with the data significantly affected participants'

subjective ratings of comprehensibility and the usefulness of feedback. This shows that interactivity is a key component for designing a more preferable and usable visualization tools.

Although the existing flaws reduced in 2D and 3D feedback was significantly more than the textual and no feedback, there was no significant difference between the 2D and 3D feedback or textual and no feedback. While performing the task in 2D and 3D, participants spent significantly less time interpreting the feedback and locating the flaws in the original design. Participants spent a majority of their time redesigning the model. On the other hand, textual and no feedback required more time to locate the flaws in the original design and then redesigning them. The redesigning time of the model alone after locating the flaws is independent of the modality of the feedback and is attributed to the participant's designing skills. This is the likely reason why the existing flaws removed in 2D and 3D were not significantly different. The same reasoning can be applied to textual and no feedback.

This study was limited to 20 minutes per trial which resulted in some unexpected results. The difference in performance between 2D and 3D, and likewise, between textual and no-feedback could have been surfaced if there was no restriction on time to redesign the part models. If no time restriction is applied, it is expected that participants will converge to a better design faster in 3D compared to 2D. Similarly, participants will converge to a better design faster in textual than in no-feedback. The performance, in terms of the redesign time, will be even more prominent if the design task is iteratively performed, where participants improve their designs iteratively, in such a situation, getting feedback in 3D is expected to produce significantly better performance than all the other modalities, and providing no feedback would result in more design iterations and consequently more time to completion. This type of the study is an area of future work.

To summarize, this study compared the effect of the modality of manufacturability feedback on design engineers' design performance, usability and workload. A novel feedback tool was developed and tested for usability. The study confirmed that modality of feedback is expected to have an effect on design engineers' performance, usability and workload. Feedback given in 3DIF, although similar in performance and workload to 2D, is expected to be more preferable and usable to the users due to its high interactivity.

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APPENDIX A. PRELIMINARY QUESTIONNAIRE

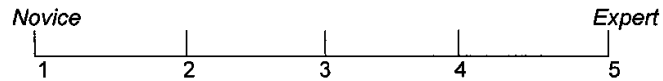
Preliminary Questionnaire- Student

*Demographics and Preliminary Questionnaire***Demographics**

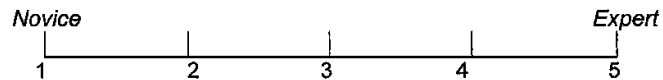
- 1 What is your age?
- 2 What is your gender? Male Female
- 3 Major
- 4 Year
- 5 Casting classes taken

Casting Experience

- 6 How many years of experience do you have in casting design?
- 7 How many parts approximately have you designed?
- < 10 10 - 50 >50
- 8 On scale of 1 to 5, where 5 is an expert in casting design. How much would you rate yourself as a casting designer?



- 9 On scale of 1 to 5, where 5 is an expert in casting design. How much would you rate yourself as a casting designer?



- 10 What are the types of parts you design? (e.g. brackets, engine blocks etc)

Preliminary Questionnaire- Student

11 What is the level of supervision or guidance needed by you when you design?

12 Do you rely on software-based casting analysis tool to review your designs?

Yes No

If the answer is NO, skip to Question 13.

a. How long (approximately) does it take to get the design reviewed?

b. What **types of issues** in your design are identified in the feedback **from the analysis software** and how are these analysis results **represented in the feedback**? Use numbers 1 through 5 to rate the **ease of interpretation** (where "1" is very difficult to interpret and "5" is very easy to interpret) and **usefulness of feedback** (where "1" is not at all useful and "5" is very useful).

CASTING ANALYSIS	REPRESENTATION MODE				EASE OF INTERPRETATION *					USEFULNESS OF FEEDBACK **				
	Text	2D	3D	Oral	1	2	3	4	5	1	2	3	4	5
Isolated Heavy Section														
Consistent Cross Section														
Core Area														
Draft analysis														

* 1 = least interpretable
5 = highly interpretable

** 1 = least useful
5 = highly useful

13 Reply If you answered NO to Question 12
How do you analyze your design for manufacturability?

Preliminary Questionnaire- Student

14 List the types of casting processes that you are aware of?

15 List all the types of casting defects that you are aware of?

APPENDIX B. TRAINING QUESTIONNAIRE

TRAINING QUESTIONNAIRE**Feedback**

1. **What types of analysis will you be given feedback on, check all that apply**
 - a. Visibility Analysis
 - b. Consistent Cross Section Area Analysis
 - c. Draft Analysis
 - d. Undercut analysis
 - e. Core Area Analysis
 - f. Isolated Heavy Section Analysis
 - g. Hot Tear Analysis
2. **2D Visual Feedback has 6 views for each type of analysis result: True / False**
3. **All Cores in 3DIF are represented as red solid surface: True / False**
4. **Consistent Cross Section in 3DIF is represented as spheres: True / False**
5. **All Cores are represented in a single table in Text Feedback: True / False**
6. **The location of features is represented as coordinate positions in Text feedback: True / False**

Analysis:

7. **Constant Cross Section refers to area with uniform thickness which results in potential feeding problem. True / False**
8. **For Isolated Heavy Section, its total number is the only factor that drives its cost in the design: True / False**

Goal:

9. **Your goal is to redesign part regardless of the weight of the final design: True / False**
10. **You are allowed to use any CAD features you like: True / False**
11. **Final design should be within bounding envelope of a reference model: True / False**
12. **You are allowed to use simulation tools to check the stress constraints: True / False**
13. **You will be given feedback in all of your trials: True / False**
14. **You are not allowed to change the dimensions of the *Interfaces* shown in the design: True / False**

Post-Trial Questionnaire – Student

Post-Trial Questionnaire

1. How would you rate your confidence level in the final design of your part for the above trial?

○ ————— ○ ————— ○ ————— ○ ————— ○

Very Confident Confident medium confident Unconfident Completely Unconfident

2. How would you rate the quality of the redesigned part in terms of meeting the given design specifications?

○ ————— ○ ————— ○ ————— ○ ————— ○

Very High High Medium Low Very Low

3. How would you rate the complexity of the original design?

○ ————— ○ ————— ○ ————— ○ ————— ○

Very Simple Simple Average Complex Very Complex

4. How difficult was it to redesign the model?

○ ————— ○ ————— ○ ————— ○ ————— ○

Very Easy Easy Average Difficult Very Difficult

5. How would you rate the ease of navigation of the feedback tool?

○ ————— ○ ————— ○ ————— ○ ————— ○

Very Easy Easy Average Difficult Very Difficult

6. How would you rate the comprehensibility of the feedback for the 3 types of casting analysis result?

Analysis type	Level of comprehensibility				
<i>Consistent Cross Section</i>	<i>Very Comprehensive</i> <input type="checkbox"/>	<i>Comprehensive</i> <input type="checkbox"/>	<i>Average</i> <input type="checkbox"/>	<i>Incomprehensive</i> <input type="checkbox"/>	<i>Very Incomprehensive</i> <input type="checkbox"/>
<i>Isolated Heavy Section</i>	<i>Very Comprehensive</i> <input type="checkbox"/>	<i>Comprehensive</i> <input type="checkbox"/>	<i>Average</i> <input type="checkbox"/>	<i>Incomprehensive</i> <input type="checkbox"/>	<i>Very Incomprehensive</i> <input type="checkbox"/>
<i>Core Area</i>	<i>Very Comprehensive</i> <input type="checkbox"/>	<i>Comprehensive</i> <input type="checkbox"/>	<i>Average</i> <input type="checkbox"/>	<i>Incomprehensive</i> <input type="checkbox"/>	<i>Very Incomprehensive</i> <input type="checkbox"/>

APPENDIX D. POST-EXPERIMENT QUESTIONNAIRE

Post-Experiment Questionnaire – Student

Post Experiment Questionnaire

- 1 What strategies did you use to redesign the part?
- 2 Did you perform the task differently depending on whether you were using the text-based feedback or 2D feedback or 3D feedback or no feedback?
- 3 You have 100 points to distribute between no feedback, text, 2D and 3D visual feedback modes to measure the *comprehensiveness* of feedback for different casting analysis results.
How would you distribute the points (each row should add up to 100 points)?

CASTING ANALYSIS	NO	TEXT	2D	3D	TOTAL POINTS
Constant Cross Section					100
Isolated Heavy section					100
Core area					100

- 4 You have 100 points to distribute for each criteria between no feedback, text, 2D and 3D visual feedback modes to measure how well one mode of feedback fulfilled a criteria relative to the other mode. How would you distribute the points (each row should add up to 100 points)?

CRITERIA	NO	TEXT	2D	3D	TOTAL POINTS
Amount of information content					100
Appropriateness of Information					100
Comprehensibility of information					100

Post-Experiment Questionnaire – Student

Ease of Navigation					100
Usefulness in eliminating design flaws					100
Usefulness in learning					100
Your tool of Preference					100

5 How do you see the prototype 3D tool being used at your work environment?

6 List three things that you like about the 3D visual feedback tool

7 List three areas of improvements in the 3D visual feedback tool

8 Are there any other comments that you would like to make?

APPENDIX E. IRB APPROVAL

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
1138 Pearson Hall
Ames, Iowa 50011-2207
515 294-4566
FAX 515 294-4267

Date: 7/17/2014

To: Prashant Barnawal
428 Stonehaven Dr
Ames, IA 50010

CC: Dr. Michael Dorneich
3018 Black Engineering Bldg
Dr. Matthew Frank
3023 Black Engineering

From: Office for Responsible Research

Title: Study on Evaluation of Designer Feedback Systems in Design for Manufacturing

IRB ID: 14-265

Approval Date: 7/15/2014

Date for Continuing Review: 7/14/2016

Submission Type: New

Review Type: Full Committee

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the recruitment materials and informed consent documents that have the IRB approval stamp.
- **Retain signed informed consent documents for 3 years after the close of the study**, when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study by submitting a Modification Form for Non-Exempt Research or Amendment for Personnel Changes form, as necessary.
- **Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences** involving risks to subjects or others; and (2) **any other unanticipated problems involving risks** to subjects or others.
- **Stop all research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Research activity can resume once IRB approval is reestablished.
- **Complete a new continuing review form** at least three to four weeks prior to the **date for continuing review** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

Upon completion of the project, please submit a Project Closure Form to the Office for Responsible Research, 1138 Pearson Hall, to officially close the project.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

IRB ID: 14-265

INSTITUTIONAL REVIEW BOARD (IRB)
Application for Approval of Research Involving Humans

RECEIVED

Title of Project: Study on Evaluation of Designer Feedback Systems in Design for Manufacturing

APR 22 2014

Principal Investigator (PI): PRASHANT BARNAWAL		Degrees: Master of Science
University ID: 699466768	Phone: 412-736-2339	Email Address: prsnt@iastate.edu
Correspondence Address: 428 Stonehaven drive, Ames, IA		
Department: Computer Science, Human Computer Interaction		College/Center/Institute: Liberal Arts and Science, Engineering
PI Level: <input type="checkbox"/> Tenured, Tenure-Eligible, & NTER Faculty <input type="checkbox"/> Adjunct/Affiliate Faculty <input type="checkbox"/> Collaborator Faculty <input type="checkbox"/> Emeritus Faculty <input type="checkbox"/> Visiting Faculty/Scientist <input type="checkbox"/> Senior Lecturer/Clinician <input type="checkbox"/> Lecturer/Clinician, w/Ph.D. or DVM <input type="checkbox"/> P&S Employee, P37 & above <input type="checkbox"/> Extension to Families/Youth Specialist <input type="checkbox"/> Field Specialist III <input type="checkbox"/> Postdoctoral Associate <input checked="" type="checkbox"/> Graduate/Undergrad Student <input type="checkbox"/> Other (specify:)		

FOR STUDENT PROJECTS (Required when the principal investigator is a student)		
Name of Major Professor/Supervising Faculty: Dr. MICHAEL DORNEICH		
University ID: 112329217	Phone: 515-294-8018	Email Address: dorneich@iastate.edu
Campus Address: 3028 Black Engineering, Ames, IA		Department: IMSE
Type of Project (check all that apply): <input checked="" type="checkbox"/> Thesis/Dissertation <input type="checkbox"/> Class Project <input type="checkbox"/> Other (specify:)		

Alternate Contact Person: Dr. Matthew Frank	Email Address: mfrank@iastate.edu
Correspondence Address: 3023 Black Engineering, Ames, IA	Phone: 515-294-0389

ASSURANCE

- I certify that the information provided in this application is complete and accurate and consistent with any proposal(s) submitted to external funding agencies. Misrepresentation of the research described in this or any other IRB application may constitute non-compliance with federal regulations and/or academic misconduct.
- I agree to provide proper surveillance of this project to ensure that the rights and welfare of the human subjects are protected. I will report any problems to the IRB. See Reporting Adverse Events and Unanticipated Problems for details.
- I agree that modifications to the approved project will not take place without prior review and approval by the IRB.
- I agree that the research will not take place without the receipt of permission from any cooperating institutions when applicable.
- I agree to obtain approval from other appropriate committees as needed for this project, such as the IACUC (if the research includes animals), the IBC (if the research involves biohazards), the Radiation Safety Committee (if the research involves x-rays or other radiation producing devices or procedures), etc., and to obtain background checks for staff when necessary.
- I understand that IRB approval of this project does not grant access to any facilities, materials, or data on which this research may depend. Such access must be granted by the unit with the relevant custodial authority.
- I agree that all activities will be performed in accordance with all applicable federal, state, local, and Iowa State University policies.

Prashant Barnawal 4/22/2014, [Signature] 4/21/14
 Signature of Principal Investigator Date Signature of Major Professor/Supervising Faculty Date
 (Required when the principal investigator is a student)

- I have reviewed this application and determined that departmental requirements are met, the investigator(s) has/have adequate resources to conduct the research, and the research design is scientifically sound and has scientific merit.

Janis Terpenning Janis Terpenning 4-22-14
 Printed Name of Department Chair/Head/Director Signature of Department Chair/Head/Director Date

For IRB Use Only	Full Committee Review: <input checked="" type="checkbox"/>	Review Date: July 15, 2014
	EXPEDITED per 45 CFR 46.110(b): Category Letter	Approval/Determination Date: July 15, 2014
	Approval Not Required: <input type="checkbox"/>	Approval Expiration Date: July 14, 2016
	Not Research: <input type="checkbox"/>	
No Human Subjects: <input type="checkbox"/>	Not Approved: <input type="checkbox"/>	Risk: Minimal <input checked="" type="checkbox"/> More than Minimal <input type="checkbox"/>
IRB Reviewer's Signature <u>Kenny A. Aguilera</u> July 17, 2014		