Improving Design and Manufacturing Performance
Through Advanced Visualization

By
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Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering in partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Mechanical Engineering

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Abstract

Visualization technology is advancing at an impressive rate, and Raytheon is investing heavily in the technology to improve product performance and manufacturability. Raytheon Missile Systems (RMS) has recently upgraded their visualization space, called a CAVE (Computer Aided Visualization Environment), to a state of the art facility with over 500 square feet of advanced visualization screen space. This is part of an overall corporate effort to improve visualization capabilities; there are similar facilities in Massachusetts and Australia, with plans to add more in Alabama, Texas, and beyond.

The RMS CAVE contains a stereoscopic 3D display with cutting edge immersive technology for large scale 3D visualization of hardware and facilities. The CAVE hosts a wide variety of design review events across the whole product lifecycle focused on product design and manufacturing, as well as facility / factory modernization. This work explores the use cases taking place in the CAVE, both established and experimental. Established use cases are design for manufacturing and assembly (DFMA) reviews, facility reviews, and demonstrations. New use cases introduced include 2D data immersion reviews, and VR based training.

Despite the strong value that the CAVE was providing to those who used it, it was underutilized. The CAVE utilization was only 30%-50% at the inception of this work, leaving ample capacity to host additional events. The focus of this project is to understand and leverage the RMS CAVE in Tucson, AZ to its full potential by increasing utilization and maximizing the value of meetings taking place in the CAVE.

To do this, we document the value proposition, and identify novel use cases to improve utilization and effectiveness of the CAVE. The CAVE value proposition is comprised of five main elements – immersive 3D, visual real estate, collaboration and engagement, context and decision making, and improved efficiency. The CAVE has historically been used as an immersive 3D environment, and this is reflected in the current use cases, which heavily leverage 3D content. While immersive 3D content is valuable, user research reveals that the ability to have a large amount of critical information in one place is just as important.

To leverage this underutilized capability, the Immersive Design Center (IDC) team held four brainstorming sessions to identify relevant events that could be enhanced through use of the CAVE. Implementation of recommendations from these brainstorming
sessions has resulted in a utilization increase from an average of 32% to an average of 67% in only a few months. Furthermore, analysis indicates the majority of this increase is a result of newly identified use cases. Qualitatively, groups have been more engaged, and collaboration has been much stronger than in a traditional meeting space.

These qualitative benefits materialize into tangible savings, with comparable facilities recouping initial investment costs in only six months. Raytheon has identified specific savings related to design for manufacturing and assembly (DFMA) reviews, laser scanning and facility reviews, and increased meeting efficiency. Results indicate that meetings are running 30% faster in the CAVE when compared to a traditional meeting space.

We also explore a case study in virtual reality training, considering the application, customer feedback, and the business case. Feedback was positive, but there are several business strategy factors to consider including development costs, updates due to assembly process improvements, and commercial structure.

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Glossary of Terms

4K – 4 times standard HD, 2160 x 4096 pixels
AR – Augmented Reality
CAD – Computer Aided Drafting
CAVE – Computer Aided Visualization Environment
DFA – Design for Assembly
DFM – Design for Manufacturing
DFMA – Design for Manufacturing and Assembly
GPU – Graphics Processing Unit
HDTV – High Definition Television
IDC – Immersive Design Center
IDS – Raytheon Integrated Defense Systems
LAN – Local Area Network
LCD – Liquid Crystal Display
LGO – Leaders for Global Operations
LIDAR – Light Detecting and Ranging
MRP – Manufacturing Resource Planning
PC – Personal Computer
RAM – Random Access Memory
RMS – Raytheon Missile Systems
ROI – Return on Investment
VR – Virtual Reality
1.0 Introduction

Advanced visualization is growing rapidly, and companies like Raytheon are capitalizing on this trend to develop a competitive advantage. Advanced visualization centers are playing a key role in this transformation. These collaborative spaces enable engineers, factory workers, and managers to have meaningful conversations through the common language of visualization. These environments empower individuals to speak their minds and provide perspectives that would normally go unexpressed.

1.1 Background

The Raytheon website says “Raytheon Company is a technology and innovation leader specializing in defense, civil government and cybersecurity solutions. Founded in 1922, Raytheon provides state-of-the-art electronics, mission systems integration, capabilities in C5I (command, control, communications, computing, cyber and intelligence), sensing, effects and mission support services.”¹

Raytheon Missile Systems (RMS) has recently upgraded their visualization space to a state of the art facility with over 500 square feet of high resolution screen real estate. This is part of an overall corporate effort to improve visualization capabilities; there are similar Raytheon CAVE facilities in Massachusetts and Australia, with plans to add more in Alabama, Texas, and beyond. The map in Figure 1 shows Raytheon’s global visualization footprint. Raytheon has found significant value in these visualization facilities, and has an interest in maximizing their impact. These facilities, known as ‘CAVEs’ (Computer Aided Visualization Environments) are used across the product lifecycle; Figure 2 identifies key points in the product lifecycle where the CAVE adds value.
The focus of this project is to understand and leverage the RMS CAVE in Tucson, AZ to its full potential. This involves increasing the utilization of the CAVE, and maximizing the value of meetings taking place in the CAVE.
1.2 Problem Statement

The RMS CAVE required significant time and resources to construct, and has resulted in a state of the art visualization tool for the company. The Immersive Design Center (IDC) team has historically hosted a wide variety of engagements using the CAVE, with the majority falling into three main categories. The primary types of reviews in the CAVE have been Design for Manufacturing and Assembly (DFMA) reviews, facility reviews, and demonstrations.

A DFMA review is a focused review on a particular design and/or manufacturing problem, with the goal of reducing cost and improving quality and manufacturability. These reviews focus on a wide variety of information ranging from 3D models to cost analyses. Facility reviews are 3D reviews, often featuring stereoscopic capabilities, which transport an audience to a facility with proposed changes alongside existing facilities. This gives participants a strong sense of what the facility will look like when finished, and helps identify changes early before construction begins. Finally, demonstrations are events where customers, employees or other guests are shown the visualization capabilities of the CAVE.

CAVE users have reported significant value in the CAVE, and have often scheduled follow-on visits. Despite the strong value that the CAVE was providing to those who used it, at the inception of this project the RMS CAVE was underutilized. With CAVE utilization at only 30%-50%, time to host additional events remained. The IDC team sought a way to increase utilization, and deliver additional value to the company.

1.3 Hypothesis and Method

To inform our hypothesis, we interviewed 30 individuals within RMS from diverse backgrounds. These interviews revealed common themes, which form the basis for the CAVE value proposition. The CAVE value proposition is comprised of five main elements – immersive 3D, visual real estate, collaboration and engagement, context and decision making, and improved efficiency. Immersive 3D is the most salient feature of the CAVE that caused participants to associate this feature most strongly with the CAVE. Although immersive 3D was front of mind for most individuals, there was an
even stronger response in favor of visual real estate, although few thought of this as the primary reason for the existence of the CAVE. This understanding provided the insight needed to develop a hypothesis - that the CAVE had been focused heavily on leveraging the immersive 3D capabilities, while placing less emphasis on its ability to effectively show large 2D datasets.

To test this hypothesis, the IDC team organized several brainstorming sessions with the goal of identifying reviews that could take advantage of the CAVE's visual real estate without necessarily using the immersive 3D features. This thesis explores this primary hypothesis. Based on results from proposed and executed additional reviews focused on visual real estate rather than 3D immersion, this thesis argues that indeed such use cases can substantially expand the value of CAVE technology.

1.4 Thesis Structure

Chapter 2 begins with a review of literature, examining CAVE architecture, use cases, and data visualization techniques. Chapter 3 covers the specific RMS CAVE architecture, as well as optimal strategies for CAVE usage. The value proposition is covered in detail in Chapter 4, including return on investment (ROI), and utilization. Chapter 5 considers use cases, including DFMAs, facility reviews, data immersion reviews, and demonstrations. Each section describes the use case, benefits from the CAVE, and specific examples. A VR Based training application is then reviewed in Chapter 6, describing the effort and feedback gathered. Finally, Chapter 7 presents conclusions and recommendations, providing actions that can be taken in the future.
2.0 Review of Literature

The purpose of this chapter is to review current studies related to CAVE technology and visualization. CAVE architecture is explored starting with the first mention of CAVE architecture up through recent developments in visualization. Various use cases for the CAVE are explored, as well as the benefits of large scale visualization.

2.1 CAVE Technology

CAVE technology has been in use for several years, with various architectures considered throughout the years. This section will survey three major developments in CAVE technology, including the original CAVE, large LCD walls, and the CAVE2.

2.1.1 The Original CAVE

Cruz et al. were the first to introduce the concept and coin the term CAVE in their 1992 paper. They introduce a Virtual Reality (VR) system designed to immerse individuals within a virtualized world. They note that the CAVE was originally developed not as a video game platform or flight simulator, but as a visualization tool for science. In a follow on paper in 1993, Cruz et al. describe the setup as a cube shaped apparatus having images projected onto three walls and the floor. The cube shape is used to approximate a sphere, avoiding the complexities of creating a spherical projection. The system was powered by a cluster of five computers, one per projector plus one more to coordinate between them. It was equipped with wired head and hand tracking for changing perspective and physical interaction. Users donned 3D glasses to enable stereoscopic 3D. Each projector had a resolution of 1280*512 pixels per eye, and operated at 120 Hz.

The original CAVE paper focused on the 3D nature of the device, and introduced it as a new type of VR. They described the benefits in these terms:

1. Suspension of disbelief – a term borrowed from the film industry, described as giving in to a simulation, and ignoring the medium itself. This is key to the audience believing the simulation and getting past the novelty of the experience.
2. Viewer centered perspective – The CAVE tracks the user and maintains a perspective consistent with their movement, convincing them they are in a virtual world.

3. Immersion – “the degree of visual simulation a VR interface provides for the viewer – the degree of the suspension of disbelief”
   a. Field of view – represents the viewing angle an individual can see without rotating their head.
   b. Panorama – The viewing angle an individual can see with head rotation
   c. Viewer centered perspective – The ability of the system to update the virtual world to account for movements in the user’s head
   d. Body and physical representation – representation of the user’s body, which is avoided with a CAVE system as they are physically there
   e. Intrusion – The level blocking out the outside world, with a CAVE, this is not an issue

2.1.2 Large LCD Walls

While the CAVE was designed to view large scale 3D data, developments in LCD technology led to the LCD wall, which is focused on displaying large scale 2D data. Leigh et al. describe the developments in large LCD walls as arrays of multiple flat panel displays that act as a single large screen with very high resolution. The evolution of powerful graphics and PC clusters has continued to increase visualization quality and make large displays like LCD walls more accessible. These advances are made possible in part by the consumer gaming market and HDTV market, where companies are investing heavily to move the technology forward.

Technology is transforming the way that scientists and engineers are studying a wide variety of phenomena. Visualization helps individuals to verify the validity of a model, display results more quickly, and better communicate the results to outside parties. One advantage of the LCD wall is that everyone has access to the relevant
information. Additionally, each participant is aware of who is in the room, and that they all have access to the information.\textsuperscript{5}

They found that the work performed in these facilities resembles the work done in paper based project rooms. Spending ample time to prepare the information properly is important to the effectiveness of the meetings. By arranging the information in different ways, participants found that they could develop new insights about the data.\textsuperscript{5}

\section*{2.1.3 CAVE2}

While the original CAVE architecture continued to advance, a new design emerged that maintained the immersive visualization while using a new architecture. In 2012, Febretti et al. introduced the CAVE2, a new architecture for the CAVE system.\textsuperscript{6} Rather than utilizing projectors, the CAVE2 consists of flat panel LCD TVs arranged in a cylindrical shape. The system is 24’ in diameter and 8’ tall, consisting of 72 TVs. The resolution is 37 megapixels per eye, with the displays polarized for optimum viewing at various positions. The architecture required a 36 computer cluster plus a head node to coordinate them.\textsuperscript{6}

The CAVE2 enabled new types of hybrid use cases, using both 3D and 2D data. The CAVE2 can be used for fully immersive 3D, dedicated 2D mode, or in a hybrid mode with a mix of 2D and 3D data. The authors claim that this system is the first of its kind with the ability to visualize 2D and 3D data in this way before. While the prior CAVE design is effective at 3D visualization, it does not have sufficient resolution to be effective for 2D designs. Large scale LCD walls are effective for 2D visualization, but are not as effective at immersion due to the walls being completely flat. The CAVE2 design combines these into a single design, enabling both uses.\textsuperscript{6}

\section*{2.2 CAVE Use Cases}

Several papers discuss different strategies and applications for the CAVE, and demonstrate practical applications and usage scenarios. The CAVE was originally built for 3D purposes, and this is demonstrated by the uses Cruz et al. propose in their 1992 paper, some of which are listed below.\textsuperscript{7}

1. 3D modeling of regional-scale weather
2. Interactive 3D vector fields
3. Interactive 3D modeling of biological macromolecules
4. Graphical planning for brain surgery
5. Modeling of the evolving universe

Creagh writes about using CAVE technology to showcase products to potential customers. The US Army assembles cross functional groups in the CAVE to see the current design and identify potential problem areas. Soldiers are brought in to provide an end user perspective, and identify any issues that may have been missed by the engineering team.

Boyles and Fang describe a data driven system for representing 3D data in a CAVE environment. They present an immersive environment that enables the users to intuitively look around, move behind data, and manipulate the data with physical interaction. The system allows for real time scaling, filtering of data and isolation of data subsets for further examination.

Song and Norman describe their efforts to model the complex scale challenges present in our universe with the aid of VR technology. They explain that the universe is structured at many levels, from star systems that are a few light years apart, to galaxies that are hundreds of thousands of light years across, to groups of galaxies that are hundreds of millions of light years apart. They use numerical simulations, and augment simulations by visualizing these structures in a VR environment. The ability to traverse the simulations across time, space, and scale provide a more meaningful picture of the dynamics across large scales.

Leigh et al. describe several examples, including a research effort to map a lake in Antarctica. The project collected data on the lake including bathymetry, chemistry, and biology. Using a large LCD wall they visualize the bathymetry in stereo 3D side-by-side with 2D scatterplots of biological and chemical information. The large display and combined data availability are found to help the team better understand both the bathymetry and how biological and chemical factors vary across the lake.

Leigh et al. also describe a group of ecologists working to understand the navigational patterns of ants. While ants by nature only navigate in two dimensions, the group used stereoscopic 3D to add a time dimension to the navigation charts, giving
researchers additional cues to understand patterns. The large display space and 3D perspective is found to give the entomologists the breadth of data they need in order to consider several individual trajectories, allowing them to think about the whole problem instead of needing to continuously cycle through different trajectories.\textsuperscript{11}

### 2.3 Large Scale Visualization Benefits

Reda et al. consider the benefits of using larger displays to view data.\textsuperscript{12} These include viewing multiple related datasets, avoiding switching windows, and improving focus. Since typical displays do not have more than four megapixels, there are required design tradeoffs, and do not allow for the visualization of very large data sets, or multiple datasets. They assert that traditional CAVEs are not effective at 2D data exploration, and are intended for 3D data exploration. Alternatively, large LCD walls are not well suited to 3D environments, but excel at 2D data display. The CAVE2 combines the ability to show multiple datasets with the immersive 3D capabilities of a traditional CAVE.\textsuperscript{12}

Andrews and North describe an experiment that measures the effectiveness of using a large display to work through disparate data.\textsuperscript{13} Their goal is to determine if individuals can be more effective at “sensemaking” tasks, bringing together different pieces of information to determine a novel conclusion. They observe that the additional space helps to better make sense of the information.\textsuperscript{13}

Ni et al. find that increased display size and resolution improve task performance.\textsuperscript{14} The experiment uses a factorial design and treats size of display and resolution separately. They report improvements due to both size and resolution for navigation, search and comparison activities.\textsuperscript{14}

### 2.4 Stereoscopic 3D

McIntire and Liggett describe stereoscopic 3D and how it works.\textsuperscript{15} Even 2D images still have certain 3D clues present, such as occlusion (one object blocking part of another), relative size, and shadows. These cues help the brain discern the relative depth of each object. Stereoscopic 3D adds binocular disparity, or simultaneously
showing two different images to each eye. The brain then interprets these slightly different images to determine the relative depth of each object.\textsuperscript{15}

McIntire et al. review the body of studies on stereoscopic vs. non-stereoscopic 3D, measuring how effective each is. The study finds that in 60\% of the cases considered, stereoscopic 3D improves performance.\textsuperscript{16}
3.0 Visualization Technology at Raytheon

This chapter explores visualization technology at Raytheon, discussing the state of technology and describing CAVE architecture. The chapter also explores how the CAVE is used from a practical standpoint, as well as optimal strategies for CAVE usage.

3.1 Prior CAVE Installations at Raytheon

Raytheon first decided to build an immersive visualization space in 2010, similar to the original CAVE architecture described by Cruz et al. in their 1992 paper. The CAVE was located at Raytheon Missile Systems (RMS) in Tucson, AZ. The CAVE was a trifold design that could be moved depending on the configuration, shown in Figure 3.

![Figure 3: Original RMS CAVE](image)

In 2013, IDS in Andover, MA decided to create a CAVE as well. They went with a CAVE2 design. This enabled more 2D data reviews, due to the much higher resolution. The CAVE2 is pictured in Figure 4.
In 2016, RMS decided it was time to upgrade their technology. They considered multiple alternatives, both the CAVE2 design, as well as a design using projectors. They decided on a hybrid design, using the best properties of projection and LCD screens.

3.2 RMS CAVE Setup

The current hybrid RMS CAVE consists of two main elements, the main display, and the LCD wall, as shown in Figure 5. The main display of the CAVE is the seven panel projection surface with stereoscopic 3D capabilities, measuring 38’x11’, plus two projectors aimed at the floor. The screens are arranged in an arc to save space and maximize visual real estate. Each screen has a 4K projector with stereo 3D capabilities. The LCD wall is made up of 55” 1080p LCD TVs arranged four high by five wide.

The main CAVE display is powered by multiple sets of computers, allowing the team to set up two different meetings and easily switch between them; the LCD wall is powered by a separate computer. The main control mechanism is via wireless keyboard and mouse; both the LCD wall and main display have separate keyboards and mice. For demonstrations, a wireless video game controller is often used to control the demonstration.

The CAVE is equipped with nearly every software package that a typical employee would have at their workstation. This includes office products, document
readers, CAD programs, media players and scheduling software. Additionally, the system is setup so users can log in, and access the online systems they are authenticated to use with their account. Additionally, the company LAN is accessible to facilitate easy file transfer. The CAVE has access to the company model management system as well, so any model can be pulled up if a participant has the drawing number. Both the main display and the LCD wall have wireless video inputs to allow participants to mirror their laptop display onto the CAVE. These features enable individuals to access and share the information they need to hold an effective review.

Most often, a facilitator will set up and run the CAVE, allowing the meeting organizer to focus on the meeting rather than on managing the technology. Some organizers receive a brief orientation to the controls for the CAVE and are able to run the meeting themselves, only requiring help from the facilitator if something goes wrong.

For remote collaboration, the room is equipped with a room scale video and audio teleconference system. The entire CAVE display can be shared with another CAVE facility, or specific programs can be shared with individual remote computers participating in the meeting. The lights, teleconference, and display are all set up using a touchscreen controller located within the CAVE.

The room itself is large enough to accommodate 40-70 people, depending on the configuration. It is important to be able to accommodate a large number of individuals to enable large collaborative events. High-top tables and chairs are the main seating, which encourage participants to stand up and move around the room.
3.3 Optimal CAVE Usage Strategies

The CAVE requires a paradigm shift to be used most effectively. While most media are linear in nature, the CAVE is a parallel environment, allowing for multithreaded discussions. In a conventional single screen presentation, a presenter pulls everything together into a cohesive document, determines the order to present, and controls the flow of content.

The CAVE requires presenters to think differently. Instead of segregating the relevant information into sequential slides, presenters should take that same information and arrange it in native format (e.g., spreadsheets, documents, pictures, CAD models, etc.) in the CAVE. This gives participants access to all of the data at once, rather than them needing to remember everything said on the slides. The most effective meetings take advantage of this, and structure accordingly. A presentation can be a single data point, but that should be one data point among many. It is often beneficial to hold a dry run of the meeting a few days beforehand to develop a content display strategy, and determine what, if any, additional information is required to facilitate an effective meeting.

Using multiple datasets has several advantages, as the data is dispersed throughout the room, and can be viewed by everyone in the room. Since the flow of
information is not controlled by a central person, there is far more room for creative exploration and unstructured discovery. With the information available for everyone to see, the meeting is more agile and can accommodate changes in direction more easily. The CAVE allows enhanced collaboration and creativity, because when it is used correctly, the space produces spontaneous conversation. Instead of picking exactly what will be talked about, in what order, the CAVE supports the ability to have a wide variety of information, with the ability to dig deep into any aspect of that information.

Many times a participant needs to have more than just one piece of information to make a determination. If the scope of available information is narrow, it can be difficult to come up with answers without requiring follow up. If data and experts from a diverse set of disciplines are readily available, answers can be determined on the spot and the meeting can continue to flow effectively. Having all the information up at once helps to keep the discussion on track as well. When conversations wander onto unproductive tangents, other participants can point to the rest of the available information to redirect the conversation to more relevant matters.

Cross functional representation is important, as each group brings a different perspective to the problem at hand. The combination of data and expertise from diverse backgrounds leads to novel solutions that would not otherwise come up.

When diverse information and expertise are present in the CAVE, an interesting behavior emerges. Small groups will often form in front of different areas of the CAVE, each discussing a separate idea. Furthermore, since they are not limited to the information right in front of them, they have context for the whole problem. This serves to multiply the effectiveness of the CAVE by generating multiple sets of ideas that can then be brought together to produce even more ideas.

The CAVE is better suited for creative and collaborative sessions than for linear presentations. In the Tell/Sell/Consult/Join spectrum, the meetings best suited for the CAVE are more participatory in nature, on the consult and join end. If there is minimal participation from the audience, there is likely little value in the CAVE. The CAVE allows for spontaneous changes in direction; when a linear flow is most appropriate, the CAVE may not be much better than a regular meeting room.
In certain cases, only a portion of a meeting will greatly benefit from the CAVE. As an example, for a DFMA review, the participants often spend the first hour or two orienting themselves to the DFMA process and the project. If this is done with videos and a single presentation, it is possible to use a regular conference room for this portion if the CAVE is needed for another engagement.

### 3.4 Example Layouts

To illustrate these principles, this section provides contrasting examples to demonstrate effective CAVE usage. Meetings typically have a focal point, often a presentation or a model, with additional context surrounding that focal point. The surrounding context can be anything from agendas, to requirements, analyses, or other data that supports the main point. These augment the main point, which is usually built from a limited perspective, and provides a multifaceted lens to view the information from. A large part of the value in the CAVE is providing context for the data being reviewed. By properly communicating the context, participants are empowered to contribute more fully which results in enhanced collaboration.

To take a DFMA as an example, in a traditional conference room, one would create a slide deck with screenshots of the model, specific drawings, background information, and so forth. This will lead to a linear discussion that is focused on whatever the current slide is. To fully leverage the CAVE, the organizer should figure out which native files are required, and lay out the information accordingly.

For instance, an effective meeting might have three versions of the 3D model pulled up: one is the full assembly, another is an exploded view, and the third is a cross section. It is important to work with the relevant design engineers to agree on the model layout, as they have the best understanding of the model. Participants can then manipulate the model as needed, hide and unhide parts, or even pull up new assemblies if needed.

On another section of the CAVE, there may be pictures of the actual hardware, showing what it looks like in reality. The process flow for the factory can be included as well, highlighting key process steps or bottlenecks. A spreadsheet documenting the cost of each part provides participants the ability to understand what parts are most
important, and helps quantify the benefit of simplifying or removing a part. Having an agenda present helps participants to be aware of the meeting timing, and keep things flowing. A list of DFMA principles can be pulled up to help spark new creative ideas.

The meeting goals and objectives take up another portion of the screen, and maintain focus on key objectives. A spreadsheet is present to document all relevant ideas that come out of the meeting. Additionally, if there is physical hardware available, it is good practice to bring this in to provide another perspective. Figure 6 shows how this might be laid out on the RMS CAVE (figure is to scale).

![Diagram of Main CAVE Display and LCD Wall]

**Figure 6: Example of an effective CAVE Layout**

The point is not to use these exact file types, or even this layout; the point is to have diverse information in native file format. In contrast to a traditional presentation, a slide may have a diagram of the factory flow, but if the specific details for a process step are not shown, they cannot be accessed without requiring some sort of follow up. Furthermore, that information is only available when that slide is being discussed.

Organizers need to treat the CAVE differently than another space, otherwise, the meeting will not see as much gain from the environment. Many reviews do not take advantage of the CAVE as it is intended to be used, and use it much like a regular
conference room. Figure 7 shows a layout that is much less effective, as it is not leveraging the native files or the visual real estate of the CAVE. The layout is essentially a regular presentation, with a view of the model thrown in for good measure. Meetings that are set up in this fashion are typically much less effective than those leveraging the full capabilities of the CAVE.

![3D Model (Full assembly)](image)

![Presentation](image)

**Figure 7: Example of an Ineffective CAVE Layout**

The difference between these layouts reflects not only a visual change but a procedural change as well. With the second layout, the meeting will move in a very linear fashion, with participants looking at the same data for the majority of the time. With the first layout, to tell a proper story, the presenter must make use of the entire room, and participants are free to make connections that the presenter may not have even thought of. Additionally, during brainstorming time, organic groups often form in front of different datasets, and they will come up with independent ideas. This multiplies the effectiveness of the meeting, and helps to unlock new trains of thought, that when brought together can form truly synergistic solutions.
3.5 CAVE Design Considerations

A CAVE, in its simplest form, is a computer aided visualization environment (CAVE). The concept is technology independent, and can be created in different varieties. There are several considerations to take into account in a CAVE environment.

3.5.1 CAVE Visualization Considerations

CAVEs must choose a visualization medium, and the two main choices are projectors and LCD walls. The original CAVE design was done with projectors, the CAVE2 uses LCDs, and the RMS CAVE uses both. Projectors can be placed in front of the screen, or behind the screen. The main advantage to front projection is that it requires less space; the main disadvantage is that participants may cast shadows. Due to the way the CAVE is used at RMS, rear projection was selected, as participants often walk up to the screen, and shadows would have affected the experience. Each medium has different benefits and drawbacks, detailed below.

In terms of maximum screen size, and in turn minimum number of breaks in the image, projectors have an advantage. Since screens can be tiled, the main consideration here is the number of breaks in the image due to the edge of the screen, known as a bezel. Bezels break up the image, reducing the quality of the experience. Certain content, such as 2D images, are not greatly affected by this, but stereo 3D images are much lower quality when there are 2D objects breaking up the illusion of 3D imagery. For comparison, the projector panel size on the RMS CAVE main display is 5.5’x11’, compared to the LCD wall panels that are 55’ (47.9”x27”) TV screens (see Figure 8 for visual comparison). RMS chose projectors for the main display to produce the large size with a minimum number of bezels, improving the quality of stereoscopic 3D.
Rear facing projectors take up more space than LCD panels, as projectors must be far enough away from the screen. The RMS CAVE uses rear projection technology, and projectors must be several feet away from the screen to work properly. In fact, each projector uses a high quality mirror to reflect the image, to meet the space constraints of the room. In contrast, the LCD wall only requires a small access space directly behind it. RMS chose to use an LCD wall for a secondary display since a rear projector based system would not have fit in the available area.

It is important to determine the required resolution, as more resolution means more cost, but insufficient resolution can greatly degrade the quality of the experience. The first question to ask is how far away the audience will be, as this will directly affect the required resolution. For CAVE facilities, participants often walk right up to the screen, which means that the resolution needs to be very high to avoid a blurry image. The type of media is also important; specifically, text requires high resolution to be legible at smaller sizes. Coarser objects do not require as high a resolution, and one can use a lower resolution screen. One of the reasons earlier CAVEs succeeded with lower resolution is that they focused on 3D imagery, which require lower resolution than text to display effectively.
3.5.2 CAVE Controls and Computer Technology

After the display hardware is determined, the controls and interactivity are the next consideration. There are three primary types of controls – basic input/output, motion tracking, and head tracking. Basic input and output in the RMS CAVE is performed with a keyboard and mouse, coupled with a video game controller for certain demonstrations. These serve to manage the basic functions of the CAVE, including arranging windows, running programs, and manipulating models. Motion tracking is used if the facility requires physical interaction with the participants. Head tracking is more important if this is a single user experience, as it is normally used to reorient the view to match a certain individual. While the RMS CAVE is equipped with motion and head tracking technology, it is used rarely, usually only in demonstrations.

Once the visual space and environment are defined, the computer specifications can be determined. The main performance driver for CAVE facilities is the graphics, requiring powerful GPUs. The GPU is responsible for physics, spatial position, rendering, and overall graphics processing. RAM is also important, if the capacity to manage large files is required. Processing capability is also a consideration, managing the overall flow of information.

3.6 Single Node

Historically, large scale CAVE systems have required cluster computing. Previously, there were limitations, such as maximum number of outputs for a single computer, or inability to render enough pixels. The cluster got around this by having multiple computers connected to one central computer, expanding the graphics processing power and output size. Normally, there is a head node that does the main computing, and passes on much of the graphics processing to cluster nodes, that each run one or more screens.

The advantage of this system is that it has more graphics processing power, and until recently, enables using more displays than is normally possible. Cluster nodes have been specially designed for CAVE systems, and as such require complex distributed computing software tools and libraries. Therefore, the cluster setup is not supported by most software applications, and requires specially designed proprietary
software, as well as the expertise to use it. This places limitations on the types of software that can be used in a cluster system, and makes the system more difficult to use. Additionally, since cluster systems are not very common, it results in expensive software packages.

To address the issues posed by the cluster setup, the RMS CAVE team developed an innovative solution to this issue, and put the computing power of a cluster into a single computer, dubbed “single node.” This design places the power of cluster computing into a single machine, which is simpler from an architecture and usability standpoint. The computer has enough graphics cards and video outputs to run the seven 4K projectors used in the CAVE main display.

The single node allows the user to interact with the CAVE as they do with a regular computer, and can run almost any application that can be installed on a typical PC. The single node is equipped with familiar spreadsheet, presentation, word processing and web browsing applications, providing users the tools they need to run an effective meeting. Since they can use the computer in much the same way they use their own, there is very little training required to teach someone how to use it properly. This means that many meetings can be run by the organizer alone rather than requiring a dedicated operator at all times.

Another major benefit is that engineers can use the 3D modeling application they use at their desk, rather than going through the work to import the model into proprietary software. This saves a great deal of time in meeting prep, as the models do not need to be converted into a new format for use in the CAVE. This gives participants access to the very latest version of the model, which avoids confusion, and provides the ability to update the model in real time. Since there is no requirement to convert the model beforehand, if the participants need access to a model they did not think they would need, the system is able to access the company model database and display the file.

### 3.7 Future Trends in Visualization Technology

CAVE technology is the beneficiary of consumer electronics and cinema technology. Due to the rapidly increasing quality, and decreasing cost of good quality consumer electronics, CAVEs have made large advancements since they were first
built. There is a new trend in visualization starting with high quality head mounted displays, both for VR and AR. Current technology suffers from limitations such as resolution, multi-user interaction, weight, and high costs. Due to these limitations, there are difficulties using head mounted displays (HMDs) for collaborative activities, as well as for 2D data. As these devices continue to progress, they will start to be more attractive options for visualization.

Should HMD technology continue to advance, they may become commonplace enough to replace the functionality of the CAVE. If the comfort and resolution of the devices are sufficient, many of the same use cases could be ported to HMDs, likely with lower cost and better quality.
4.0 Value Proposition, Utilization, and Return on Investment

The CAVE has several benefits, which are described in this chapter. The value proposition is described first, which is comprised of the key features of the CAVE that make it unique and provide benefits relative to a regular conference room. This first section takes a closer look at the capabilities identified by the interview process, as well as direct observation. Identification of this value proposition leads to an expanded set of use cases, positively affecting utilization, which is described in the second section. Finally, the qualitative benefits identified in the value proposition materialize into tangible savings, explored in the last section of the chapter.

4.1 Value Proposition

To identify the value proposition, over 30 individuals from across the company are interviewed. Participants are from a variety of functions, including DFMA experts, program engineers, operations, and CAVE personnel. These conversations are varied, but reveal clear themes. These themes form the basis for the CAVE value proposition.

The feature that interviewees are most familiar with is the 3D immersive capability. In fact, several participants who had used the CAVE for non-3D activities apologized for not using the 3D capabilities. Another capability mentioned by almost everyone is the ability to have all relevant information in one place. Although almost everyone mentioned this, the fact that several individuals apologized for using it this way implies they see it as a secondary feature and that the main reason for the CAVE is for 3D visualization. This likely comes from the history of the CAVE, because until very recently, RMS had a CAVE that was only capable of effectively displaying 3D immersive imagery. Because of this, the most popular prior use cases were 3D based. In addition to these two capabilities, the other benefit of the CAVE that people highlighted is collaboration. Numerous individuals mentioned that the CAVE is an extremely effective collaborative space. In fact, one of the key goals of the RMS CAVE is to provide a place to facilitate collaboration. Other benefits of the CAVE noted by interviewees include improved context and decision making, as well as increased efficiency. Direct observation and analysis of CAVE meetings are also included in this section, to augment the statements made by interviewees.
4.1.1 Immersive 3D

The most prominent feature of the CAVE is the 3D immersive capability. Due to the large screen size and stereoscopic 3D capabilities, the CAVE is very effective at drawing the audience into the visualization. This is particularly valuable for facility reviews and demonstrations, where it is important to transport the audience to a new environment.

The CAVE effectively visualizes 3D designs, leveraging the capabilities of solid modeling software to visualize three dimensions. This provides depth perception and helps give a sense of what the product really is – beneficial for those who are not used to CAD. It becomes easier to see interference fits, radius problems, clearances, access issues, and ergonomic considerations.

For facility reviews, the audience will often be individuals who are not used to visualizations, and having models close to actual scale facilitates identification of problems, such as determining if a handle is placed properly. The CAVE is used to rearrange facilities before they are constructed, allowing engineers, factory managers and operators to see the factory layout before anything is moved, and results in fewer changes in the future and subsequently less cost.

Disney uses a similar facility to see what their rides will look like before they build them. This helps engineers to rapidly prototype the rides without having to create physical structures. When participants feel immersed in the facility, they are able to see issues that would not surface in a standard meeting room.

Though stereo 3D is useful, it should not be applied to everything. For a mechanical engineering audience, the stereo 3D is often not necessary, as they are used to looking at 3D models on 2D screens. Stereo 3D is more valuable for those who are not used to 3D models, such as operators, finance analysts, and HR professionals. Some individuals experience discomfort in the CAVE in 3D mode. This ranges from motion sickness to others who just get tired of the glasses after a short time and take them off.
4.1.2 Visual Real Estate

Although not the most prominent feature, the ability to leverage the visual real estate of the CAVE is the most commonly cited benefit by interviewees. For discussions that require a large amount of data (e.g., model, list of action items, cost, drawings, simulations, etc.), the CAVE allows participants to have access to all of the relevant information without requiring the presenter to switch between multiple items.

The CAVE features over 500 square feet of high resolution visual real estate, and can support a wide variety of software applications. The CAVE can display a great deal of information on the screens from several perspectives and disciplines. Rather than looking at one aspect of a problem, the team can see a wider aperture of information. When this is combined with cross functional representation, brainstorming is enhanced and participants generate insights more effectively. Additionally, by having several native files up at once, rather than static images, the conversation can move in different directions and support the dynamic nature of a group discussion.

The visual real estate can be used to display several files, as well as to display large files. Certain file types, such as schedules, process flows and complex spreadsheets may require the entire CAVE display to view effectively. By displaying a much larger portion of the file, participants are able to see the bigger picture, and easily move from one portion of the file to another. For schedules, rather than looking at one small part of the schedule, the entire team can see the impact of moving out one activity, and watch the effects five years into the future, for example. On a process flow, the team can trace the part from receipt at the factory all the way to loadout, without needing to stop to change the view. This provides incredible insight into the network, and gives teams the ability to iterate faster, looking at a larger segment of the problem at one time.

4.1.3 Collaboration and Engagement

While the visualization capabilities of the CAVE are the most obvious feature, the true power of the CAVE lies in enhanced collaboration. The CAVE has the visual and physical real estate to accommodate large quantities of people and information. As mentioned before, this enables groups to have access to all the required information,
making discussions move more effectively, and enabling greater creativity. Since space is available, teams are able to invite participants who are not as close to the problem at hand, providing valuable insight that would be lost otherwise.

People behave differently in the CAVE, in a way that is not seen in other environments. Notably, people often stand in CAVE reviews, rather than sit down. There is a strong tendency to walk up to the screen to state an idea, or point to data across the room to keep things moving. This is encouraged by the very large displays, and high top tables.

As mentioned before, there is a tendency to break up into smaller groups during brainstorming sessions, produce creative ideas, and come back together. Normally this behavior leads to a meeting breaking down, but due to the layout of the CAVE, it is easy to bring everyone back together and build on these ideas. Indeed, discussions stay on track more effectively in the CAVE; since all of the relevant information is available, it is easier to refocus the conversation. This also allows for divergent conversations, leading to ideas that would have never been discussed in a regular meeting that goes sequentially through a presentation.

Despite the fact that CAVE meetings are large, many times including over 30 participants, we have found that people remain focused throughout the meeting. It is rare to see people zoning out, checking their emails or scrolling through their phones during meetings. People normally remain involved with the meeting, and eager to provide their input.

The CAVE is equipped with remote collaboration capabilities, giving participants the ability to expand the meeting beyond the CAVE. The teleconference system enables participants to call into the meeting and hear the conversation with good audio fidelity. There are several video sharing options, ranging from live video feed, application sharing, and full CAVE to CAVE connections. These capabilities allow for participants from around the country to see what is going on in the CAVE and participate in the meeting.
4.1.4 Context and Decision Making

Reviews held in the CAVE benefit from an accelerated pace of understanding for participants. This again ties back to the large screen space, and the volume of information that can be displayed at once. The facility provides a powerful medium for communicating a wide variety of content. By having a large display canvas, it becomes easier to convey complex material. Decision making is easier because all the relevant content is available on the screen.

4.1.5 Improved Efficiency

Reviews are more efficient, as organizers are able to describe things more quickly, and provide information without laborious explanations. This results in shorter meetings, saving time for meeting participants. By inviting a broad range of individuals and displaying a wide variety of information, there is clearer cross functional communication which facilitates getting everyone on the same page.

4.2 Utilization Increase

After identifying and clarifying the value proposition, our goal is to make the best use of the CAVE. To do this we considered the unique value proposition of the CAVE, and how to leverage it in ways RMS has not in the past. As mentioned before, the CAVE has recently been perceived primarily as a 3D visualization tool, and because of this most of the utilization had been for 3D based use cases. Furthermore, almost every interviewee mentioned that it is useful to have all of their information into one place; however, the CAVE was not being heavily utilized for these types of activities.

Based on understanding of the value proposition, we organized four brainstorming sessions to find new ways of using the CAVE for “data immersion” reviews. We staged the CAVE with a variety of 2D data and explained that while the CAVE is known for its 3D capability, there might also be tremendous value in seeing large datasets. This was a paradigm shift for many participants, as they had not considered using the CAVE for anything other than 3D content. Our focus in the brainstorming sessions was to identify ways we could leverage the visual real estate of
the CAVE, with the goal of identifying specific meetings to hold in the CAVE shortly after.

There was widespread enthusiasm to pilot a variety of meetings, and several individuals were eager to participate. This resulted in a number of new reviews, ranging from on-time delivery to quality control processes. Participants found value in the CAVE reviews, demonstrated by the sustained increase in utilization and high number of return visitors. The average utilization before the brainstorming sessions was 32%, while the average utilization afterwards increased to 67%. Furthermore, the primary driver for this increase was due to 2D data / collaboration reviews, increasing from an average of 4% to 31% over the same time period. Figure 9 illustrates the change in utilization before and after implementing new 2D use cases, showing an improvement in both overall utilization and for 2D data / collaboration reviews.
4.3 Return on Investment

While the CAVE has clear qualitative benefits, these also materialize into quantitative benefits. Raytheon has calculated the return on investment for its CAVE facilities, and has found that they provide attractive returns. While exact numbers cannot be disclosed, the information below should provide the reader with an appreciation of the impact.

DFMAs are a key contributor to the ROI for the CAVE. While the exact numbers are not public, Raytheon reported that they hold hundreds of DFMAs and this has resulted in millions in savings over a three year period. Due to the benefits of the CAVE, DFMA reviews are more effective. Based on an analysis of DFMAs held in the CAVE environment, Raytheon has determined that the CAVE is responsible for 25% of the savings generated by DFMA reviews in the CAVE. That is to say, an additional 25% savings is created by using the CAVE for DFMA reviews, compared to the savings generated in a more conventional DFMA review. This 25% represents a significant savings when the frequency and impact of DFMA reviews are considered.

Meetings also move faster in the CAVE. By taking a sampling of 10 different meetings, and having organizers estimate how much time it would have taken outside of the CAVE environment, we estimate that there is approximately a 30% time savings for meetings held in the CAVE. With an average meeting size of 15, and a utilization approaching 100%, this represents a large cost savings.

Raytheon has realized significant savings through laser scanning and immersive 3D facility reviews. These projects typically return savings many times larger than the time required to create the laser scan and model. The Rhodes group reports that laser scanning can save 7%-10% on total facility cost over traditional methods.

The best analog for overall CAVE performance is from a close competitor working on comparable products. Lockheed Martin has a similar facility to the CAVE that they use for design reviews, human factors, and virtual prototyping, similar to the RMS CAVE. They reported a $5 million initial investment in the technology, with $10 million in savings per year using their facility.
5.0 Use Cases

The CAVE supports a wide range of use cases, with the most important described below. These use cases are DFMA, facility reviews, demos, and 2D data immersion reviews. DFMA reviews, facility reviews, and demos have been important use cases since before the CAVE was renovated, while 2D data immersion reviews were not very common before the start of this work. 2D data reviews became much prevalent in the CAVE during the course of this research, and are projected to maintain a position of importance going forward.

5.1 DFMA

Raytheon started using the design for manufacturing and assembly (DFMA) process in 1999, and since then it has become a well-established process within Raytheon. Steudel et al. state “the DFMA objective is to develop the best product or process that meets all requirements, has competitive quality and cost, while avoiding foreseeable downstream problems.” These downstream problems can include manufacturing, integration, testing, and sustainment problems that are often overlooked by product design performance focused engineers. The DFMA process starts with identifying a specific problem to solve and identifying the relevant information and correct individuals to address it. The team then schedules a workshop, brainstorms ideas, and determines which ones to implement.

5.1.1 DFMA Background

Boothroyd and Dewhurst describe the DFMA methodology in their book. Design for manufacturing and assembly is a combination of design for manufacturing (DFM) and design for assembly (DFA) methodologies. The goal of DFM is to determine the best way to design the parts so they have high quality, and the goal of DFA is to ensure that the design enables one to put them together efficiently. They describe three main reasons for performing DFMA reviews:

1. To provide guidance to the design team, facilitate a simpler product, and drive lower manufacturing and assembly costs
2. Benchmark the design vs. competitors’ products
3. Develop ‘should-cost’ models for negotiation with suppliers

The two main goals of DFMA reviews (often referred to simply as DFMAs), are to reduce the number of parts, and therefore reduce the number of assembly operations, and to make the assembly operations easier. These two principles, along with other techniques described by Boothroyd and Dewhurst, have helped drive savings for a wide variety of industries, including automotive, defense, consumer electronics, and medical equipment. The automotive industry has reported huge gains from DFMA, helping popularize the methodology. Ford claimed billions of dollars in savings and GM benchmarked vs. Ford and helped close a 41% productivity gap, using DFMA approaches.25

It is important to start DFMA activities early, as making changes becomes more expensive as the design or production progresses. Several techniques are detailed in the book, from design for injection molding, to casting and automation. Arguably the most important goal is to reduce the number of parts, and Boothroyd and Dewhurst provide three useful guidelines to help determine if two parts must be separate:25

1. Does the part move relative to other parts?
2. Must the part be of a different material or be isolated from other parts?
3. Must the part be separate to allow for assembly or disassembly?

If the parts do not meet one of these criteria, they should be combined into a single part.25

5.1.2 DFMA Planning

At Raytheon, the full DFMA process is typically a 45 day project. DFMA workshops begin by identifying a specific problem to focus on, such as a part being too expensive, difficult to manufacture or producing low yields. The problem could be identified through cost growth, problems in manufacturing, or an engineer seeing something that needs to change. The DFMA team then drafts a plan with a clear goal for the workshop. For example, a part may currently cost $100 and have a target cost of $80.

Once the scope is determined, the team then determines the level of effort required for the workshop. DFMA efforts range widely in scope, from a focus on the type
of fastener to the full design of a major component. There are two types of DFMA’s – regular DFMA’s, and iDFMA’s. Regular DFMA’s are full efforts and use large teams, typically for complex, high impact problems. iDFMA reviews are somewhere between a typical peer review and a DFMA – they use DFMA principles in conjunction with peer review. Full DFMA’s are for larger problems that require additional effort to solve, and usually result in larger impact. iDFMA’s are much smaller, and are not normally done in the CAVE. Ideally, all regular DFMA’s would be held in the CAVE, but this is restricted due to classification requirements. If a review contains any classified information, it cannot be held in the current RMS CAVE, and must be held in a classified area instead. DFMA facilitators at RMS normally hold all other DFMA’s in the CAVE.

5.1.3 DFMA Data Sources

As mentioned earlier, the data displayed in a DFMA meeting is important, as it sets the tone for the whole meeting. Data displayed usually includes the 3D model, drawings, agenda, objective, cost data, brainstorming lists and presentations.

Previously, to display this much information would require printing out several plotter size drawings, spreadsheets, and engineering data. The team would then need to hang this on conference room walls to show the information. Alternatively, they would cut and paste the data into a single presentation, which limits the amount of information available at a given time. Both methods do not allow for live data; this means that if the information has changed, or if there is additional detail needed, it is not available.

5.1.4 DFMA Participants

A key element to the success of the DFMA is assembling an effective team. Since DFMA’s are often solving cross functional problems, there is a significant benefit to bringing in a diverse team. It is important to have the individuals who are closest to the design, as they are most familiar with design details, adding individuals who are not as intimately involved with the problem brings new perspectives and helps identify issues or ideas that would not have come up otherwise. While it may be obvious that a DFMA requires engineers and factory managers, there is value in the perspectives of those coming from assembly, supply chain, finance, contracts, suppliers, and other
functional areas and groups. These individuals bring unique perspectives and can point out ideas that will be missed by those who are too familiar with the problem.

One goal is to find problems that were not apparent before, and this often happens by bringing in a diverse group of people. As an example, when looking at a complex cast part, having casting experts in the room can uncover the fact that it would be more effective to machine the part than to try to cast it. On the assembly front, having trained assemblers available can point out elements of the part that would be very difficult to assemble.

Leveraging the synergistic effect, the “magic” of the review happens through bringing together a great deal of information, combined with a diverse crowd to produce the greater result. This group is then able to look at the information and create a rich discussion based on the data available. The CAVE is uniquely suited to this type of discussion as it requires both room and screen space, which the CAVE can provide.

5.1.5 DFMA Event

DFMA reviews are typically two four-hour sessions, one in the afternoon the first day, and one in the morning the second day. The workshop is split up like this to give participants a chance to digest the information from the day before and come back with new insights the next day. The workshop starts out with an overview of the project, model, and the particular problem that needs to be solved. The facilitator then covers the DFMA principles, to provide a framework for participants to follow and help spark new ideas during the workshop. The principles Raytheon uses are listed below:  

1. Minimize the number of parts and obsolescence  
2. Minimize the use of fasteners  
3. Standardize / commonality  
4. Avoid difficult components  
5. Use modular assemblies and subassemblies  
6. Use multifunctional parts  
7. Minimize reorientations  
8. Use self-locating features  
9. Avoid special: tools, test, and support equipment
10. Design and provide accessibility
11. Minimize process steps
12. Design for service life and reliability
13. Minimize footprint in the field
14. Design for exportability
15. Ergonomics and safety

5.1.6 Brainstorming

After the overview is complete, the team moves into the brainstorming session. Participants are encouraged to provide ideas with little regard for whether they make sense. Others may build on the idea to continue to define it, or develop new ideas entirely. Once the ideas are defined, the facilitator records them and encourages the group to move on. It is important to get a variety of ideas, both simple and effective, such as changing from a custom cutter to a standard radius, to radically new ideas like changing from machining to casting. These “crazy” ideas do not always result in workable options, but often inspire other ideas that do work out.

Participants consider a variety of factors, from the cost of a part, logistics cost, assembly cost, and more. Ideas can range from different material processing, material choice, or part geometry. Participants need to question what is actually adding value: for example, is paint required, or will bare metal suffice? Considering ways to leverage commonality across product lines can simplify supply chain logistics and reduce the design and manufacturing costs for a part as well.

Supplier capability is another lens to view the workshop through. When Raytheon was working with a supplier in Turkey, they discovered that the supplier was very effective at sheet metal stamping and bending. Based on that information, they focused the workshop on figuring out how to take milled parts and replace them with formed sheet metal.

5.1.7 Idea Ranking

Once the team has generated a sufficient number of ideas, the workshop moves on to the evaluation phase. Each idea is ranked on two separate dimensions – impact, and ease of implementation. Based on these two criteria, the team determines which
ideas to pursue further. The facilitator uses a standard template, ranking the two dimensions on a 1-5 scale (5 is best), and multiplying them together to determine the priority. Once the best ideas are selected, they are assigned to a responsible individual who works to implement the idea.

5.1.8 DFMA Benefits from the CAVE

The CAVE provides several benefits to the DFMA process that are not realized elsewhere. The major benefit is the visual real estate, as it provides a conduit for displaying a large volume of information at once. Additionally, since the native source files are accessible, changes can be made in real time instead of needing to have follow ups.

The immersive 3D capability, as illustrated in Figure 10, enables participants to have a better appreciation for the models, and notice things they would otherwise miss. If a part has many internal features, the team can view it from a completely different perspective. The CAVE provides the ability to create "virtual prototypes" as Raytheon often does not have a chance to prototype before production needs to start. The CAVE's size and stereoscopic capabilities provide a perspective on the size of the part, helping participants understand the challenges related to handling, accessibility, routing, logistics, and serviceability.

Within the ecosystem of the collaborative CAVE environment, the designer can utilize CAVE to more clearly illuminate details for diverse groups that may include manufacturing personnel, and engineers from multiple disciplines. The CAVE helps describe the design performance and systems level reasons why certain critical features are in the design so contributors throughout the value stream can understand the context. This cross functional community awareness can lead to generating a diversity of ideas leading toward better designs and error proofed methods in manufacturing and yield higher quality product delivered in production.
Figure 10: Immersive Capabilities of the CAVE

It is possible to hold DFMA meetings outside the CAVE, but it is not as productive. When running DFMA meetings outside the CAVE, it is harder to keep everyone focused. Teams are only able to look at one thing at a time, and are unable to make connections between multiple data sets. Additionally, facilitators have found that people are more likely to come to meetings when they are held in the CAVE.

5.1.9 DFMA Examples

To illustrate how the CAVE benefits DFMA reviews, several examples are discussed. These reviews each demonstrate how the CAVE is used for DFMA reviews and illustrate the capabilities of the CAVE described previously.

Program A

The Program A DFMA is an excellent example of a successful DFMA in the CAVE. It started with laying out the information well, with multiple models, pictures, work instructions, drawings, and physical hardware. The meeting began with the typical DFMA overview, communicating the problem at hand, and reviewing DFMA principles.

The goal of the DFMA was to increase the flexibility of a particular wire in the product, to avoid test failures. The group started out together and brainstormed several ideas. At a certain point in the review, individuals started gathering around different screens, some in front of the model, others in front of the drawings, and others with the hardware. After these side conversations, the group came back together to document
the new ideas and continue brainstorming. The discussion was very rich at this point, and it was this portion of discussion that ultimately resulted in a simple idea that fixed the problem.

The second day of the workshop could not be held in the CAVE. The meeting was markedly different, and participants did not come up with any new ideas. The first day in the CAVE resulted in dozens of ideas, while the next day resulted in none. This may have been due to other factors, but it is arguably due to the environment: the CAVE is a better, more collaborative and creative place for DFMA reviews.

**Program B**

In contrast, one of the least effective uses of the CAVE was during the Program B DFMA. The room was set up with different model shots, but they were almost never referred to during the meeting. The main focus of the meeting was on a single presentation that had been prepared beforehand. Additionally, the organizers had an extremely narrow scope for the DFMA, and this resulted in most ideas being out of scope. Furthermore, most ideas that fit within their scope were deemed not feasible, and therefore not considered. It became clear that this meeting was less of a brainstorming session and more of an informational meeting. The meeting did not produce any ideas that resulted in meaningful changes to the product. This combination of not taking full advantage of the visual real estate, and tight control of the conversation limited the effectiveness of this review.

**Program C**

Program C was targeting significant cost reductions, and held a series of DFMA workshops both internally and with suppliers. The team held over 20 workshops and developed more than 600 potential action items based on these activities. The activities were not being closed out in a timely manner, and several people were moving on to new assignments. The team organized a series of meetings in the CAVE to gain stakeholder input alignment, and to determine a path forward. Due to the high level of supplier involvement, supplier representatives were invited to the meeting to provide input and gain understanding.
The team leveraged the CAVE to rate potential action items in terms of ease of implementation and potential impact. They considered a range of issues and ideas, from parts that could be installed incorrectly, and strategies to limit use of wet epoxy with alternatives like laser welding. They used the CAVE to display all the relevant information needed to make a good decision, including spreadsheets, models, and presentations. The CAVE provided the team with the flexibility they needed to respond to unexpected questions by pulling up new files using the available screen space. They could more effectively answer questions by speaking with a visual aid rather than just giving a verbal answer.

After they determined the action items to be implemented, the team entered everything into the existing RMS peer review tool for implementation. One participant commented that this was one of the most efficient meetings they had ever had.

**Program D**

Program D had a mold that was approaching end of life, and the program team wanted to figure out the best way to replace it. Additionally, there were manufacturing difficulties, so the team wanted to explore alternative designs for the part. Previously, the taskforce facilitators had struggled to get all stakeholders to align on a path forward. The CAVE enabled them to bring everyone into the same room to discuss the solution. Previously, meetings consisted of 6-8 individuals to gain alignment, and constantly ran into problems due to needing input from someone who was not present. With the CAVE the organizers were able to get 30 people in the room, eliminating problems due to lack of input. Due to the significant amount of visual real estate, the team could display more information and more effectively communicate the background then they could have otherwise. By holding the workshop in the CAVE, the program was able to achieve alignment on a path forward, and saved one to two months of project schedule by using the CAVE.

**5.2 Facility Reviews**

Raytheon also uses the CAVE to review proposed facility construction projects. This includes construction of new facilities, expansion of old facilities, and bringing in new equipment. For retrofitting facilities, laser scanning is used to map out the existing
facility. Once the facility is scanned, proposed expansions or equipment can be placed into the model, and a team gathers in the CAVE to review the proposed facility changes. During these reviews people may find interferences, incorrect drawings, fit problems, ergonomic issues, or other problems that had not been previously identified.

5.2.1 Laser Scanning

The process starts with laser scanning. Laser scanning utilizes LIDAR imaging to generate a high fidelity representation of a 3D space. Previously, projects made use of drawings and manual measurement techniques, which are not as effective as laser scanning. Drawings are often not updated to reflect reality, and thus there are often several discrepancies between as-is condition and the drawings. Additionally, drawings often do not provide information on height, which can be an important consideration. Manual measurements take significant effort, and provide only sparse data on the existing environment, whereas a laser scan provides a highly detailed representation. Raytheon uses laser scanning tools that are accurate to within 1-2 millimeters, providing a high level of confidence in the results.

When a facility is being upgraded or modified, it is important to understand the existing state, so late changes do not occur because of inaccurate information. When installing large equipment, sometimes it is not certain whether it will fit. Laser scanning provides much greater certainty in determining if a particular layout will work.

Once the scan is done, a laser scan professional processes the data and turns it into a point cloud. A point cloud is a set of data points that represent the space that was scanned. The data points have three dimensions plus the color. Once the point cloud is ready, the proposed facility changes are superimposed onto the point cloud.

5.2.2 Facility Reviews in the CAVE

Once the facility scan is complete, and proposed changes have been merged into the point cloud, the team holds a review with the relevant individuals. Various stakeholders are brought in, including engineers, factory managers, and assembly workers. Once the team has a chance to see the proposed layout in immersive 3D, they are able to provide feedback regarding areas of improvement. These reviews often surface problems with the design that would otherwise have required changes after the
project is complete, which is far more expensive than if they are implemented before work begins.

The CAVE provides an immersive 3D environment that gives participants a much better feel for the facility being modeled. Rather than needing to orient an assembler to a 2D drawing, the engineer can simply point at the full scale model of the facility and the assembler knows exactly what they are looking at. This provides the opportunity to see how they react and understand their concerns, rather than focusing on making sure they understand the design. This greatly improves communication between the engineers and the factory, leads to fewer changes and defects, and increases the chance of on-time implementation.

5.2.3 Benefits

Facility layout reviews are one of the best uses of the stereoscopic 3D immersive capabilities of the CAVE. Of all the use cases, the strongest positive response for stereo 3D was for facility layout reviews. The combination of life scale facilities combined with the depth perception provided by the 3D glasses heightens the sense of realism for participants. This enables them to make decisions and see improvements that would normally be overlooked on a drawing or even a 3D model on a computer screen.

The team has explored doing the 3D layout on regular computer screen, and it was not the same. When looking at a screen, the facility does not feel real, and the space is much harder to understand. Rather than showing 3D images on a regular screen, the team tends to show 2D sections of the laser scan if it is on a small screen.

The CAVE has supported much faster iterations, and far more effective layout of facilities. In the past, teams needed to create cardboard models in the parking lot to achieve a sense of realism. With the CAVE, projects can move much more quickly, and providing participants with a 3D virtual mock up is much faster.

5.2.4 Examples

When Raytheon was developing their new Huntsville facility, senior management requested that the project team design the building virtually before construction began. Rather than waiting until construction was in progress, the team laid out all of the equipment virtually using CAVE technology, as illustrated in Figure 11.
major design change, going from overhead cranes to automated guided vehicles. Hundreds of individuals contributed to the effort, making hundreds of changes, such as moving emergency exits, and reconfiguring test bays to ensure they fit. This effort resulted in having no major changes to the layout after construction, a rarity for this type of work.

![Figure 11: Model of the Huntsville Factory in the CAVE](image)

**Facility A**

For a new facility, Facility A, there were questions about whether a particular piece of hardware could flow through the entire factory. Raytheon spent a great deal of effort explaining why it would work, and were not able to convince the customer. The IDC team created a simple 3D animation showing the hardware making its way through the factory, and upon seeing this, the customer understood immediately that it would work.

**Facility B**

Facility B was introducing new hardware into the factory, and Raytheon needed to determine if this new hardware could be transported through the entire facility. Drawings indicated that the hardware would not fit throughout the factory, and that a particular test chamber would need to be moved to accommodate the new hardware. To check this, the facility was laser scanned and the proposed hardware was placed into
the scan point cloud. This scanning and modeling effort uncovered that the proposed hardware would in fact fit through the factory as is, which meant that the test chamber could remain in place. This represented a large savings as the factory did not have an available spot to move the chamber to. This use of the CAVE avoided the cost not only to move the chamber, but also to rearrange the factory to accommodate the chamber in a new location.

Facility C

Facility C was being repurposed, and new equipment was being brought in to support a different program. To review the proposed solution, the team laser scanned the facility, and arranged models of the new equipment being placed in the factory. The team then held a review in the CAVE involving engineers, factory workers, and factory management to comment on the layout. They identified several changes, including where to put power drops, test equipment locations, and work bench arrangements. This work helped avoid rearranging the factory twice per original plan, and after issues would have been encountered upon early physical testing, and enabled production to start four months earlier than expected.

5.3 Demonstrations

Along with engineering applications, the CAVE is also used for demonstrations and customer engagements. In fact, the first major meeting at the renovated RMS CAVE was for the Raytheon Board of Directors. This meeting showcased the technology that Raytheon is working on and provided them context for the RMS products. Prospective employees commonly tour the CAVE, where they gain an appreciation for the cutting edge technology Raytheon is investing in. During the summer, Raytheon also brings in school age children to get them excited about a career in engineering, and the CAVE is an excellent way to do that.

Demos have several benefits. For current employees, it serves as a marketing tool for the CAVE itself, where individuals can learn how they might be able to use the CAVE. It serves as an effective sales tool for prospective customers, demonstrating the advantage Raytheon has in visualization technology.
The key feature of the CAVE for demonstrations is the immersive 3D capabilities as shown in Figure 12. Since the room is able to create stunning visuals, demonstrations are very impressive. This gives Raytheon a powerful tool for winning new business and attracting new talent.

![Demonstration in the CAVE](image)

Figure 12: Demonstration in the CAVE

### 5.4 2D Data Immersion

The prior three use cases leverage the 3D immersive capabilities of the CAVE. As mentioned previously, this is likely due to the history of the CAVE, since it has traditionally been used as a 3D tool. These use cases made up the majority of prior usage of the CAVE, and indicate there is an opportunity to leverage different 2D capabilities of the CAVE. There had been a few people who had been doing this, but most individuals did not think the CAVE was supposed to be used for 2D activities. When asked directly, one of the key features individuals like about the CAVE is the ability to have all their information into one place and display simultaneously. As mentioned earlier, by encouraging participants to utilize the CAVE for these 2D data immersion reviews, utilization subsequently increased significantly. For more on these reviews, please refer to Section 3.3 Optimal CAVE Usage Strategies.
5.4.1 2D Data Immersion Reviews

2D data immersion reviews can take many forms, and several examples are provided below. An effective 2D data review is distinguished by the use of disparate types of data. If all of the relevant data is present at once, the team is able to be much more effective. The most important capability that these reviews take advantage of is the large amount of visual real estate.

2D data immersion reviews are more widely applicable than 3D reviews, as not all data has been brought into 3D yet. Groups from across the company, including human resources, operations, quality, engineering, safety, and more have found ways to perform these reviews. Any group with a large amount of data can make use of the CAVE when it is used properly.

5.4.3 Examples

Several new ideas surfaced based on brainstorming sessions intended to increase utilization of the CAVE. The following examples were identified, in some cases indirectly, by the brainstorming sessions. These ideas illustrate how the CAVE can be used to explore large 2D datasets.

On Time Delivery Improvement

One idea that came out of the brainstorming sessions on new uses of the CAVE was to discuss on time delivery performance. To address this, a meeting was organized in the CAVE with 25 attendees (about half were Director level). Raytheon takes on time delivery very seriously, and is aiming to improve. The CAVE was staged with relevant information, about 15 files which took up the vast majority of the viewing area. The information included strategic goals including on time delivery performance and how Raytheon is graded on it, Pareto charts showing the most common causes of late delivery, and the breakdown of where each program and each factory stood with respect to on time delivery. At the tactical level there were spreadsheets that detailed what items were late and on time, dashboards showing status of late purchase order placement, as well as other details.
The discussion was very well attended, with representatives from production control, supply chain, factory management, product lines, and more that led to effective discussion. There were several key follow ups, including meetings to align on metrics, and Manufacturing Resource Planning (MRP) use. The discussion on metrics aims to bring together each of the groups to discuss what data sources they are using, as well as which reports they are creating. The meeting brought out that there are two teams generating similar reports, but based on different data sources and going to different audiences; this meeting is intended to fix this. There was widespread agreement that maintaining compliance with MRP deadlines was a key goal in achieving on time delivery. To achieve this, several issues need to be addressed, including imperfect data, inconsistent application of standards, and disagreement on usage procedures. The follow-up discussion on MRP will help align the teams to make the system work for them, fix existing problems, and improve data integrity.

There were several notable behaviors in the meeting. The most noticeable was how engaged the crowd was. This was a meeting of 25 people, which often turns into an unproductive conversation. On the contrary, the group was highly engaged, standing up to see the screens better, listening intently to the presentation, contributing to the conversation and moving the discussion forward. Even more telling was the fact that not a single person was staring at their phone, working on their computer, or looking bored. The meeting was scheduled for an hour, but only two to three people left at that point because there was so much to talk about - most attendees stayed for another half hour to finalize proper follow ups.

The meeting flow started by looking at the strategic objectives, moving on to the breakdowns by factory, and finally looking at tactical options. A few times the discussion started to degenerate into unproductive tangents, but the group was able to refocus quickly due to the presence of the whole picture. The presenter moved from one end of the display to the other as he discussed the topics. After the main presentation was over, the group settled in to talking about several tactical items to address. One of the most interesting observations was by a participant who was looking over to another part of the screen with the strategic objectives on it. He refocused the conversation from the low level tactics by pointing to the other side of the room where the strategic objectives
were in plain sight. This sort of behavior is much less likely in a conference room where those slides would be gone and forgotten.

Finally, it is worth noting that this type of meeting, with this group of people, had not happened before at RMS. Based on the richness of the discussion and the quantity of follow up items, it is clear that there was immense value in the meeting. There was widespread agreement that the meeting was a success. One of the participants commented that this was the most productive meeting she had been to in a long time. Without the CAVE, it is likely that this discussion would not have happened.

Based on this meeting, the operations leadership team developed a strategy for managing on time delivery performance. A major part of the strategy was to hold weekly meetings in the CAVE, with separate but related topics based on the week of the month. The first week of the month is dedicated to on-time delivery performance as measured by the company. Week 2 is dedicated to MRP performance, with a consistent format between factories. Week 3 is focused on the customer’s measurement of on-time performance, and helps identify any contract modifications that may be needed to stay on track. Week 4 is devoted to analysis of metrics, and working toward consistent data sources and measurement techniques. These meetings involve participants from across the country, and make use of the CAVE’s teleconference and screen sharing system.

This cadence has led to more effective meetings, and a heightened awareness of on-time delivery performance. The IDC helps foster accountability by exposing the raw data and metrics for all stakeholders to see. This allows the relevant information to be displayed at once, and helps focus the conversation on key action items and details that must be understood to ensure on time performance. The meetings have been much more efficient, and provide a deeper conversation than other environments offer. Rather than simply reporting what is going wrong, the conversations have progressed to discussing specific action items, and determining how to meet key deliverables.

Quality Control Process Improvement

The quality group held an event in the CAVE that leveraged the visual real estate in a unique way. A team of engineers from across disciplines – manufacturing, production, and quality came together to pilot a new tool being developed to improve
process control. They split into five teams of people to work through a quality validation process. Typically, the groups need to move into different rooms throughout the building because there is not enough space. Oftentimes the rooms do not have any sort of display capability, so the groups end up crowding around a laptop. By using the CAVE, the facilitators were able to accommodate all of the different groups within the CAVE, and every group had access to a large amount of space to work with.

This had several benefits for the group. The biggest advantage was the ability to have quick communication between teams: when one team discovered something important, they were able to quickly communicate it to the rest of the groups. The facilitators were more effective as well: when they needed to explain something, or point out an issue, they could speak to all groups at once, rather than traveling to each group individually. In terms of efficiency, the group was able to finish in only 14 hours, vs. the 18 hours that they took the previous time without use of the CAVE.

Change Management Enhancement

A human resources professional was leading a task force with the goal of enabling accelerated change within the organization. This was the first face to face meeting of the whole team, aiming to unify the team, set objectives, and develop a strategy.

The facilitator staged the CAVE with a diverse set of information, spanning presentations, survey results, company processes, and action item logs. During the meeting participants were able to access additional documents through the company LAN, which provided information that would otherwise be unavailable. As a result the group was able to make quicker, better informed decisions.

The organizer also commented on the room itself, saying that the high top tables helped facilitate better interaction and involvement, and that the stage beneath the main display helped add a degree of professionalism to the presentation.

Had the group held the meeting elsewhere, it would have been in a small room with a small screen. To access to the amount of data needed for the meeting, the facilitator would have needed to print everything on large sheets of paper, taking time
and limiting flexibility during the meeting. The environment would have been much more rigid, while the CAVE enabled a free flowing discussion and deeper collaboration.

**Factory Strategic Roadmap Review**

The manager in charge of factory capability strategy developed a detailed roadmap for each factory, and wanted to communicate it to a large audience. The roadmap includes program requirements, tasks, and factory capabilities. A presentation with specific plans and tasks accompanied the roadmap, detailing factory capabilities, goals, and focus areas. The presentation described the requirements and needs, and the roadmap showed how it fits into the plan, so it was critical to have them side-by-side. As a result, this required far more space than is available on a traditional display. The organizer held the meeting in the RMS CAVE, and was able to accommodate the full timescale of the roadmap, as well as show the related presentation at the same time.

This was the first time that all six make centers presented their strategic plans to operations leadership. The organizer searched for a suitable venue to hold the meeting, and found that the only room that would support this meeting effectively was the CAVE. Another space had a large enough screen, but the bezels were too large and distracting to have a quality presentation. The CAVE provided high quality visualization of the data and gave participants the information they needed to understand the whole picture.

This was the largest meeting ever held in the CAVE with 60 people attending (75 planned), and there were still some who were not invited due to space constraints. To accommodate larger audiences, the organizer suggests making similar, scaled back visualization facilities for this type of meeting in larger presentation spaces that can accommodate a large audience and have at least two high resolution projectors.
6.0 Virtual Training

Training is an area that can benefit from advanced visualization, and the IDC team ran a pilot project to explore the technology. Carlson et al. studied the impact of virtual training, and found that it improved proficiency on an assembly task. A high volume RMS program wanted to augment their training capabilities, and engaged the IDC to develop a solution. The development process started by going to the factory floor and viewing the work. After speaking with the relevant people, the team determined that it would be best to start with a simple process – final inspection. The team then acquired video of the operation with the operator narrating the process, as well as detailed close ups of important details. This chapter will discuss the application architecture, customer feedback, and resulting changes. The business case is then discussed and important factors are considered.

6.1 Application Description

The training application consisted of four main parts - 360 photos, 360 video, work instructions, and detailed diagram overlay, as illustrated in Figure 13. The 360 video and photo portions were shot using a 360 camera, and placed into a commercially available game engine. Users can use these modes to understand the work area and see the inspection taking place. The video has an overlay with the work instructions displayed, as well as key diagrams for each step. The diagrams and photos were taken using a traditional camera, or pulled from the work instructions, and the text came from the work instructions. The user is able to navigate the video as well as view the work instructions, to understand what is needed for each step.
The tool was multiplatform capable, and was initially developed for the CAVE. This provided a great vehicle for demonstrating the capabilities of the trainer. Additionally, the trainer was deployed to a laptop computer to gather feedback from factory workers. Ultimately, the plan was to deploy to a VR headset.

### 6.2 Customer Feedback

Based on the framework proposed by Ulrich and Eppinger, a plan to gather customer feedback on the prototype was developed.\textsuperscript{29} The purpose was to gain initial user and stakeholder feedback, understand needs, gain alignment, and test our assumptions. We started by testing the tool within the IDC team, and worked out all of the obvious issues before moving to others. The most important stakeholder was the end user, the factory operator, so several workers were interviewed. The team also talked to the training group, factory engineers, factory managers, and training leads.

The overall response was very positive, with every group expressing interest in pursuing further development. The training group was excited about the application, and was interested in getting it into the factory. They mentioned compliance training, and said they were interested in updating those training modules as well. The operators
were very interested in the prototype, and all said they would be interested in using something like it for training purposes. The operators liked the ability to change the perspective and orient themselves to the work environment. They also liked that all the information they needed, from diagrams to instructions, was available in the tool.

The factory manager was interested, but expressed some concerns. He mentioned that while he liked the level of detail, he was concerned that maintaining it might be difficult. He cited that the assembly processes are updated often, and if the video needs to be reshot each time that happens, it would be too much effort.

6.3 Compliance Training

To address the issue of updating the training, the team pivoted to consider if it is possible to develop training for something that changes less often. The training group suggested compliance training, specifically torque training and crane training. These training modules are taken by a large number of people, and do not change often. This is in contrast to factory training that is highly dynamic and specific to a few individuals. These characteristics make compliance training more attractive from an ROI standpoint, as it requires less work and is applicable to more individuals.

After investigating torque training, it was determined that there was relatively little that VR training could add to what existed already. Since torque requires haptic feedback, which is possible but currently difficult to do in VR, it was determined that there was little benefit in developing a VR based training application. In contrast, crane and hoist training had several interesting options to explore for the training, from rigging, to signals, to lifting. The issue with implementing new crane training is that Raytheon does not currently do extensive hands on training, and would have required justifying the cost from a training quality standpoint.

6.4 Business Case

From an economics and operations strategy perspective, it may not make sense to create VR based training in-house. Since there are thousands of other companies that use cranes, many in a very similar way to Raytheon, it might be better to find a third party developer. Due to the huge economies of scale for software development, it will
be hard to justify building something for only one company. On the other hand, leaving
development to a third party sacrifices the chance to develop internal capabilities, which
would be valuable. If Raytheon considered alternative commercial arrangements, such
as licensing the training software, there may be a better economic case for the project.
If Raytheon could build a generic framework that is applicable to several factory
operations, the software could be licensed to several other similar companies.

While the technology is excellent and the feedback very positive, the cost of
creating and maintaining an in-house virtual trainer is high. Since there is a steep
learning curve with the software, and due to the significant economies of scale present
in software application development, there may be an advantage to outsourcing training
development.
7.0 Recommendations and Conclusion

By focusing effort on identifying use cases that leverage the visual real estate of the CAVE, the utilization has increased from an average of 32% to an average of 67%, driven almost entirely by new use cases. This is a result of the brainstorming sessions held to identify ways to use the CAVE for 2D data immersion reviews.

Below, we discuss how to maintain the current utilization rate, as well as continue to improve the value generated by the CAVE. To maintain the high utilization levels, key practices should be instituted, including regular brainstorming sessions, gathering feedback, augmenting current demos, and holding high profile meetings in the CAVE. To improve the value capture for the CAVE, organizers should be educated on CAVE usage strategies, and improved prioritization strategies should be developed.

Longer term, visualization at Raytheon would be improved by building additional visualization centers, including smaller scale venues for applications that require more than a conference room, but do not fully utilize the CAVE, as well as a space that is cleared for classified information. Finally, Raytheon should weigh different options for VR training. These recommendations are discussed further below.

7.1 Continue Holding Brainstorming Sessions

The team should continue to hold action focused brainstorming sessions at regular intervals, perhaps once a quarter. The focus of the brainstorming sessions should be on different strategic goals, aiming to increase usage and augment CAVE capabilities. These sessions will serve to keep the CAVE fresh in the minds of individuals, promoting higher awareness to keep utilization at high levels.

One focus area that makes sense to start with is 3D engineering simulation. The CAVE has powerful immersive capabilities, and this capability is currently used primarily for geometric information. Engineers have a myriad of other data visualization types, including stress, fluids, electromagnetic, and thermal analyses. A good future brainstorming session would be to organize individuals who work with simulation to determine ways to test out CAVE capabilities.

Supplier remote collaboration has been done with the CAVE, and there are opportunities to augment this capability. The team should identify a few programs that
need to meet with suppliers, and hold brainstorming sessions on how to leverage the CAVE. Some potential ideas include remote factory tours using a 3D-360 camera broadcast to the CAVE, and highly interactive long distance meetings leveraging CAVE capabilities.

7.2 Gather User Feedback

By leveraging information gathered from previous CAVE users, the unique value proposition of the CAVE was identified and compared to the current state. This information led to the actions taken during this project, and is an important enabler for the results. To continue this, the IDC should implement a regular feedback process for CAVE engagements. This could take the form of a survey, and / or personal follow up with certain organizers to understand how things went. This will keep customer understanding fresh, and facilitate identification of new strategic directions to take the CAVE in.

7.3 Demonstrations

As the CAVE becomes more popular, it may become difficult to continue holding as many demos as have been in the past. It is important to continue to do demonstrations to keep the CAVE in the minds of customers and employees. One way to maintain demos and reduce the burden on the schedule is to create standard demo times. This will help consolidate demonstrations to fixed times, improving flexibility by providing fixed times to request longer meetings to take breaks to allow for a demo. While not all demos will be able to fit into these times, many will, which will improve scheduling efficiency. Since demos are held so often, the team should further automate the demo process, to reduce burden on the staff. This will free up time for other activities.

7.4 Hold High Profile Meetings in the CAVE

While demonstrations serve to raise awareness of the CAVE, they do not always impress upon people how it can be used. Many individuals leave the demo thinking that the CAVE is only for stereoscopic 3D, which this thesis argues is not the case. To
mitigate this, the IDC should make it a priority to bring in individuals for large meetings to show the capabilities in a real meeting. A good example of this is the strategic roadmap review, where the CAVE was leveraged effectively and a wide cross section of individuals attended.

7.5 Educate Organizers about the CAVE

Using the principles introduced in Section 3.3 Optimal CAVE Usage Strategies, the CAVE team should educate organizers about how best to use the CAVE. This will help the organizer to identify the files they need in order to run an effective review. There are still reviews that do not fully leverage the CAVE, and educating organizers will help improve the quality of CAVE meetings.

7.6 Prioritization

As the CAVE becomes more popular, as it has recently, there will need to be more prioritization. Priority should go to reviews that best leverage the unique capabilities of the CAVE, namely visual real estate and immersive 3D. Organizers who are properly educated about the CAVE and plan to bring diverse data to the meeting are in the best position to hold an effective meeting. In contrast, a meeting that will consist of a single presentation and perhaps a single model should be deprioritized.

Meetings that have the strongest demonstrated ROI should have priority as well, which are currently DFMAs and facility reviews. Organizers should be encouraged to calculate tangible ROI for their meetings, and use this to demonstrate their need for the CAVE. The IDC should continue to prioritize new types of engagements to understand novel ways the CAVE can be used.

Demos are an important part of the CAVE, and must be worked in as well. As suggested before, these should happen at standard times to reduce the burden they place on the schedule.

Additionally, certain meetings, such as DFMAs, have portions that do not always need to be in the CAVE. The most important part of a DFMA to have in the CAVE is the brainstorming portion; the introduction and idea ranking can potentially be done elsewhere, as they are primarily focused on a single item.
7.7 Small Scale Visualization Facilities

Raytheon should consider investing in smaller scale visualization facilities. One area of opportunity is to create new areas based on use case. Stereoscopic 3D capability is expensive, and many of the use cases do not require it. By creating areas with large amounts of visual real estate, several meetings that would normally require the CAVE could be accommodated elsewhere. A recommendation would be to create one to two conference rooms that hold 20-30 people that have at least as much visual real estate as the LCD wall. This will open up the CAVE for more reviews that truly require the additional unique capabilities that it has available.

7.8 Classified CAVE

A recurring theme that surfaced is classified information not being allowed in the CAVE. As a defense contractor, Raytheon has a significant amount of classified information, and it cannot be used in the CAVE. There are several programs that are visually classified, or so new that they cannot be put into an unclassified space. Because of this, several DFMAs are held outside of the CAVE that would otherwise be held in the CAVE, reducing opportunities to deliver value.

In addition to certain programs being classified, there are also types of information that are classified on almost every product, such as performance data like range or radar cross section. This prevents the CAVE from hosting many meaningful simulations, which would be an excellent use of the space. Few environments can effectively visualize a large scale stereo 3D radar array, or provide a close up virtual performance test. A classified CAVE would allow for programs to test out these simulations in a collaborative environment and empower engineers to communicate their findings more effectively.

Due to the complexities of holding classified reviews in an unclassified space, Raytheon is looking at creating a classified CAVE. Raytheon should continue to pursue this effort, to enable additional types of reviews.
7.9 Virtual Training

Based on feedback from users, there is likely value in VR based training. The issue will be developing VR training for a reasonable cost. There is a cost to develop a training framework, but once it is developed, it can be leveraged widely. Therefore, it is worth considering outsourcing training development, and understanding the cost of another company creating VR training vs. Raytheon producing VR training in-house. As mentioned before, there are significant potential economies of scale for software development. Because of this, Raytheon should compare the cost of outsourcing training development with the cost of developing in house. Alternatively, if Raytheon is able to buy some of the core capability to develop a trainer, combined with in house development for Raytheon specific needs, this could provide benefits from both sides. If Raytheon desires developing these capabilities fully in house, they should consider a commercial arrangement that would allow them to license the technology to others.

7.10 CAVE Applications for Other Companies

Other companies should consider investing in similar visualization facilities, depending on their business needs. As mentioned previously, the CAVE provides several benefits, including immersive visualization, large visual real estate, and improved collaboration. The CAVE has been successful at Raytheon due to the presence of complex data requiring dynamic relationships between functions to produce successful products. Additionally, the immersive 3D capabilities have been beneficial for the many 3D applications that Raytheon pursues. While Raytheon has found value in a CAVE featuring both immersive 3D and large visual real estate, many companies would benefit by considering them separately.

2D applications have been explored most thoroughly in this project, and are the kind that most companies would likely benefit from. Companies with a need to visualize and connect complex datasets across disciplines should consider investing in a CAVE-like facility. One option that addresses the need for extensive visual real estate would be a conference room with large, high resolution 2D displays. Multiple 4K projectors would provide sufficient scale and resolution to satisfy most applications. The
applications for this space would primarily be the 2D data immersion, but activities such as DFMA's and demos could also be effective in this space. For Companies with strong 3D visualization requirements, but without a strong need for complex 2D data visualization, might consider another alternative. If 3D visualization is needed, both head mounted VR and an RMS style CAVE will provide significant benefits. Both options provide excellent visualization capabilities, but have different advantages and disadvantages. VR headsets deliver an immersive experience that enables an individual to easily change perspective and see the visualization from several angles. The CAVE provides a high resolution shared experience that gives a large group a shared view of the visualization. From an individual perspective, particularly for 3D objects, VR headsets will likely have an advantage, as they give an individual freedom to see multiple perspectives. However, for a group, a CAVE style facility would be better at the time of this writing, as shared VR experiences are still being developed, and individuals have a harder time working together when they cannot see each other. This is being addressed and may be solved in the near future, but at the moment, the CAVE is more effective for multiple users. The CAVE also has much better resolution than current VR headsets, and provides an advantage for highly detailed information such as text. There is a cost difference between the CAVE and a VR system, and VR systems are less costly than an RMS style CAVE. If the requirement is for high quality visualization, and collaboration is not a key driver, a VR system would be more cost effective. In contrast, if collaboration is important, as it was for Raytheon, an RMS style CAVE would have an advantage over VR headsets.

7.11 Conclusions

The RMS CAVE is a powerful visualization facility that delivers consistent value to customers. The platform delivers immersive 3D, visual real estate, collaboration and engagement, context and decision making, and improved efficiency. These attributes help support DFMA reviews, facility reviews, demos, and 2D data immersion reviews. By focusing on adding 2D data immersion reviews, the RMS CAVE was able to increase utilization from an average of 32% to an average of 67%. By continuing to
refine existing use cases, developing new applications, and expanding visualization capabilities, RMS will continue to capture value using large scale visualization.
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