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Assessing User Expectations of Undo in a Multi-User CAD Environment

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ABSTRACT

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Undo is a command that users rely on in most software applications. Its importance in multi-user CAD is no different. However, due to its unique nature, users may have different expectations regarding how undo should behave. This research seeks to better understand users' expectations regarding undo in multi-user CAD by having users participate in collaborative design exercises and then asking them how they would expect undo to behave. In addition, users participated in a survey in which they watched 8 videos showing users interacting within multi-user CAD and were then asked about how they would want undo to behave.

Based on these findings, various recommendations are made for how undo ought to be implemented in multi-user CAD. These include recommendations regarding the user experience/user interface as well as proposing an equation that seeks to quantify whether a user expects to share an undo stack with another user or if they should only be able to undo their own actions.

Keywords: CAx, CAD, multi-user CAD, undo, redo, UX, UI

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CHAPTER 1. INTRODUCTION

The development of multi-user CAD tools is pushing the boundaries of current engineering software technology and expanding the possibilities of engineering. Like most of the software tools an engineer uses, undo can be a powerful tool in a multi-user CAD environment. However, a multi-user 3-dimensional modeling environment is very unique compared to other software environments. As such, it is important to understand a user's expectations of how undo will perform in this unique environment. The motivation for this research is to help bring multi-user CAD to industry by helping to make it a viable option for engineers and designers. In order to achieve this, this research seeks to gain a better understanding of these expectations.

The ability to undo actions is a functionality present in most of the software that people use every day. Undo helps correct errors and ensures work is not lost or ruined due to those errors. It also provides a safety net because users know that they can go back to a previous state. This frees users to explore and experiment, leading to better creativity and more innovative solutions. Undo has become so ubiquitous, users expect it in most of the applications they use. Indeed, as Abowd and Dix state, "Few people would argue about the importance of undo" [3].

Regarding the importance of undo in CAD, French mentions, "A large engineering company recently used an analytics tool provided by BYU to track which buttons their designers clicked the most in single-user CAD. They reported to the researchers that their engineers clicked the Undo button an average of four times more than any other single button in the CAD application. This validates the importance of undo in single-user CAD, and it is likely that undo will be very important in multi-user CAD as well." Of 13,000 button clicks tracked, undo constituted approximately 18% of those clicks [4].

1.1 Problem Statement

Users' expectations of how undo should perform in a multi-user CAD environment are not well understood. Current research on multi-user undo has primarily focused on text or 2-dimensional editing systems. Even work on undo in multi-user CAD has focused on the implementation of undo rather than users' expectations of how undo should function. This research aims to provide a better a understanding of those expectations of how undo should function in these environments. In order for multi-user CAD to be widely adopted and useful in engineering practice, undo must function in such a way that does not surprise users; it must enhance the experience, not detract. Thus, understanding users' expectations is very important.

1.2 Objectives

The main objective of this thesis is to better understand what a user expects to happen when they press undo in multi-user CAD. A secondary objective is to make user experience and user interface (UX/UI) recommendations for how to implement undo in a way that best aligns with those expectations.

In order to determine these expectations, a study has been designed to determine if there are scenarios in which a user would prefer to have a shared undo stack with another user versus a local undo stack. An undo stack refers to the list of actions that will be undone when a user presses undo. When undo is pressed, the topmost action on the stack is undone and removed from the stack. In some implementations, this action is then moved to the redo stack. A shared undo stack refers to a single undo stack that is shared by two or more users. When any of those users perform an undo operation, the last action on the stack is undone, regardless of who performed it. For example, if user A created a sketch, and user B mirrored an extrude, and users A and B had a shared undo stack, user B's mirror would always be undone, regardless of whether user A or user B pressed undo. In contrast, a local undo stack means that when a user performs an undo, that user's last action is undone. Returning to the example above, if user A pressed undo and had a local undo stack, their sketch operation would be undone.

In addition to determining a user's expectations, this research seeks to better understand when people feel they are collaborating or not in a multi-user CAD environment and how that affects their expectations of undo behavior. These findings will then be used to make user experience and user interface (UX/UI) recommendations on how to implement undo in multi-user CAD to better align with their expectations.

1.3 Problem Delimitation

This research focuses on discovering what users' expectations are regarding undo. It does not study redo, though most of the literature speaks of undo and redo together. As Mancini et al. explain [5], redo may be defined as the inverse a given undo action when it is applied to a single action, but this meaning becomes less clear when talking about performing multiple undo actions. They go on to explore how redo is more nuanced and complicated than simply reversing a given undo. For example, if a user undoes multiple actions, should a redo action redo all the undone commands or just the last action that was undone? Another example: what if a sketch operation is undone? Should redo restore the entire sketch or simply recreate the first operation performed within the sketch? Scenarios such as these are worth considering, but are left as future work. Regardless, this researcher believes that many of the results and conclusions of this research are also applicable to redo.

This research also does not take into account the sketching environment of CAD. This is primarily due to the current implementation of the prototype used: sketching is still treated as a single-user environment and thus, users are unable to collaborate within sketches. Finally, this research provides a foundation upon which an implementation of undo in multi-user CAD tools can be developed, though it leaves the details of any specific implementation as proposed future work. This is due to the large scope and additional research required to implement a stable and robust solution.

1.4 Document Organization

This document is organized into the follow chapters:

- Chapter 2: Background provides a literature review and background on previous relevant work.
- Chapter 3: Method outlines how the research was performed

- Chapter 4: Results presents and discusses the results of the research
- Chapter 5: Conclusions and Future Work draws conclusions about the results, makes recommendations regarding undo, and provides a list of potential future work

CHAPTER 2. BACKGROUND

2.1 Overview

There has been much research conducted on both multi-user CAD and on multi-user undo. First, this chapter discusses multi-user undo in a general sense and then focuses on one study in particular that looked at multi-user undo on large, interactive, collaborative whiteboards. Next, it provides background on multi-user CAD and discusses current research on multi-user undo. In addition, it provides details on the current implementation of undo in NXConnect. Finally, it talks about how previous undo research provides a solid foundation upon which the current study is built.

2.2 Foundation of Multi-User Undo

Some of the most widely cited research on multi-user undo is by Choudhary and Dewan [6] [7]. In their paper "A General Multi-User Undo / Redo Model," they talk about a multi-user undo model that they implemented for a simple multi-user text editor. The concepts therein have laid the groundwork upon which much of the research on multi-user undo has been based. In their work, they outline six requirements that a multi-user model should satisfy: compatibility, independence, semantic consistency, collaboration, genericity, and the undo of arbitrary commands [7].

Compatibility refers to the fact that "multi-user undo/redo should behave like single-user undo/redo when only one user is interacting with the system, thereby reducing the overhead of learning a new undo/redo model" [7]. This enables users to incrementally learn the new features of a multi-user undo/redo model. Independence means that a user should be able to work in a collaborative session with other users, but still be able to use undo/redo without needing to coordinate with other users who may be in the same session. Semantic consistency means "the effect of undoing a command is equivalent to the state the system would be in if the undone command had never been executed." This ensures the system is always in the correct state and that that state is not incorrectly modified by the undo/redo model [7]. The collaboration requirement stipulates that a user must be able "to undo/redo commands issued by other users, thereby allowing the users to collaborate on their undo/redo." Genericity refers to the fact that the model should be generic and not coupled to a specific application. Finally, undo of arbitrary commands means that "the model must not be restricted to commands that manipulate the user-interface state. It must also support undoing of collaboration commands" [6] [7]. It is important to note that some of these requirements may be more difficult or perhaps even impossible to fulfill within multi-user CAD. For example, independence may not be achievable due to complex dependencies of CAD. Additionally, the collaboration requirement may require users to verbally communicate in order to clarify their design intent with one another.

2.3 Multi-User Undo With Large Interactive Whiteboards

One of the most relevant papers that applies to this research involves multi-user undo with large interactive whiteboards done by Seifried et al. at the University of Applied Sciences Upper Austria and the University of Waterloo. These whiteboards, shown in Figure 2.1, allow several users to work and collaborate at the same time. They work by using cameras and digital pens to record and display user input. By using these digital whiteboards, the researchers were able to capture and record the actions that their subjects took. This was invaluable to them because it allowed them to more accurately study their users' behavior by tracking the actions they took [1].

In order to better understand what users expect to happen regarding undo on these white-boards, the researchers performed an initial background study. Its primary goal was to determine which undo method best matched user expectations: local, regional, or global. These three undo models refer to the type of undo stack used. Global undo means that all of the users in the entire environment, in this case a single whiteboard, share a single undo stack; if any user issues an undo command, the last action taken by anyone is undone. Regional undo means that n number of users all share an undo stack with one another, and thus any user sharing that stack can press undo to undo the last action taken by anyone sharing that stack. In addition, regional undo deals with defin-ing which users are sharing undo stacks based on various criteria. Local or personal undo means

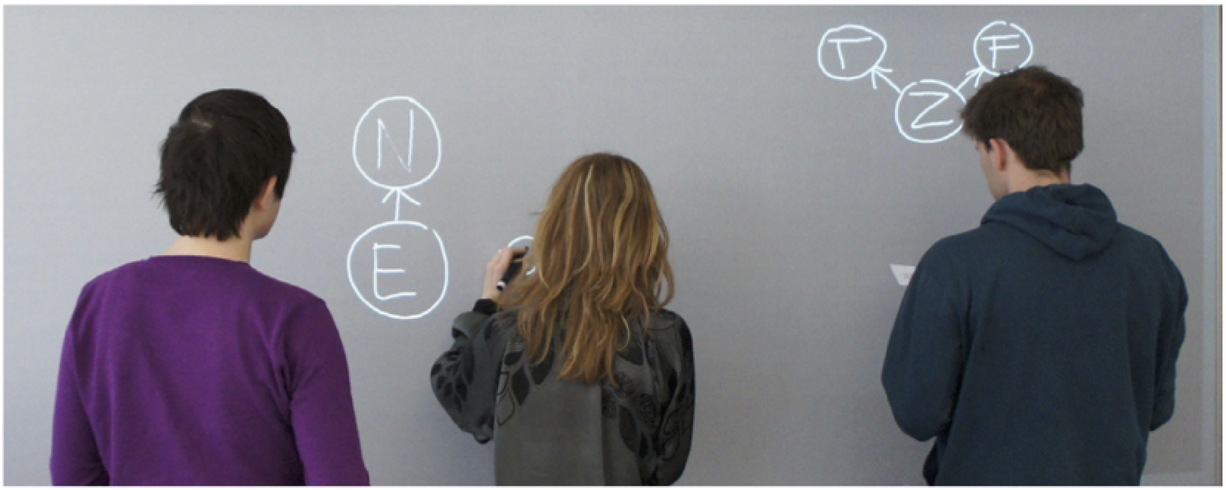

Figure 2.1: An Example of an Interactive Whiteboard [1]

that a user does not share their undo stack with any other user and pressing undo only affects their actions.

In order to determine which undo method best matched user expectations, the researchers had the subjects perform six different tasks that imitated different kinds of co-located work on the whiteboards. These tasks are shown in Figure 2.2 and include individual work, collaborative work, and a combination of the two. After completing each task, the researchers asked the participant to explain verbally what they would expect to change if they invoked a first and then a second undo action [1].

Five of the tasks involved drawing a simple directed graph and the other involved drawing a sketch. Once the subject had given their answers, the researcher would recreate the resulting graph; it was then compared to the graph that would have been created by local, global, and regional undo methods. The results indicated that regional undo aligned with users' expectations of undo behavior in most cases: 86% of the time. Local and global undo aligned with users' expectations only 47% and 22% of the time, respectively. Of note was that 5% of the time, the user's expectations could not be applied to any known undo method [1].

As a result of this initial study, the researchers concluded that if two or more people were collaborating, issuing an undo command should undo the last action taken by any of the collaborators. For example, assume users A, B, and C are collaborating to create a list of items. It does not matter if user B or C added the last item to the list; if user A presses undo, they expect the last

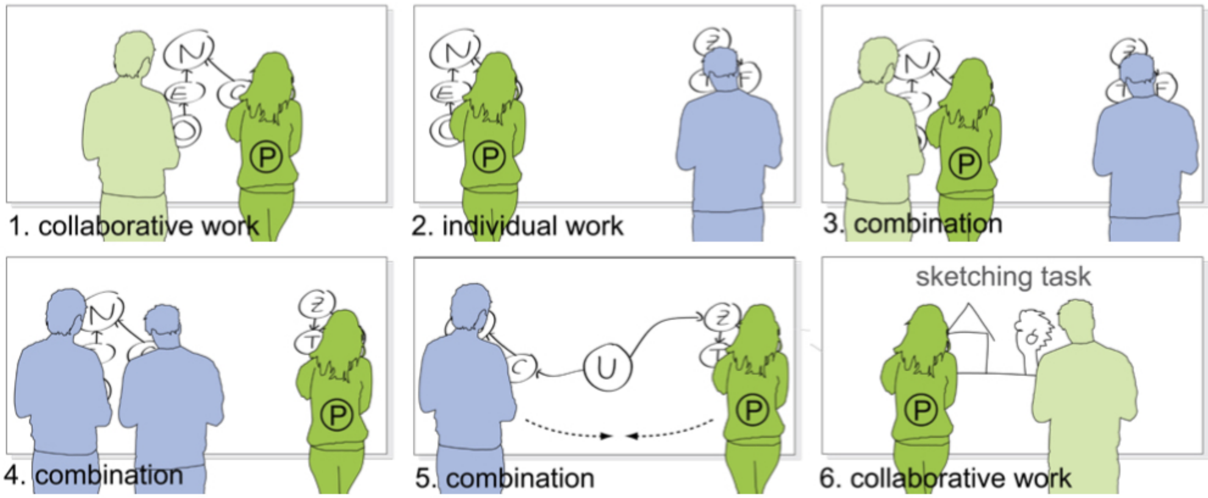

Figure 2.2: Six Scenarios Performed in the Whiteboard Study [1]

item added to the list to be undone, even if they did not add it. This also means user A would not expect their last action to be undone, which may have been an item that was added several minutes ago further up the list.

Based on these results, they wanted to determine what method of regional grouping would best meet users' expectations regarding collaboration. "Grouping" refers to how to determine if users are collaborating at a level that warrants using a shared undo stack. In order to determine this, they implemented 3 different methods of grouping collaborators together. They then performed an additional study that focused on regional undo. They first gave participants a series of tasks to complete in different collaborative settings and using the 3 different regional grouping methods. Then, they asked the participants to perform an undo at different times during the tasks by using the tool palette shown in Figure 2.3.

The 3 grouping methods were clustering, workspace, and field of view. Clustering, as its name suggests, was based on the grouping of objects that a user was editing. Items in close proximity on the whiteboard were subsequently grouped into the same region. The workspace method involved manually creating a workspace for a user. These workspaces were indicated by colored bars along the top of the screen that a user could adjust as needed. The workspaces of multiple users were also allowed to overlap with one another. The final method, field of view, involved using a Microsoft Kinect to determine how far away a given user was from the whiteboard

Figure 2.3: Close-up of the Pen and Tool Palette Used With the Interactive Whiteboards [1]

and to then automatically create their workspace based on a 125° field of view. This allowed workspaces to be determined and adjusted dynamically depending on where a user was in relation to the whiteboard. A diagram illustrating this method is shown in Figure In each of these methods, any users within the same region shared an undo stack. The researchers found that the field of view method most closely aligned with how users expected undo to behave [1].

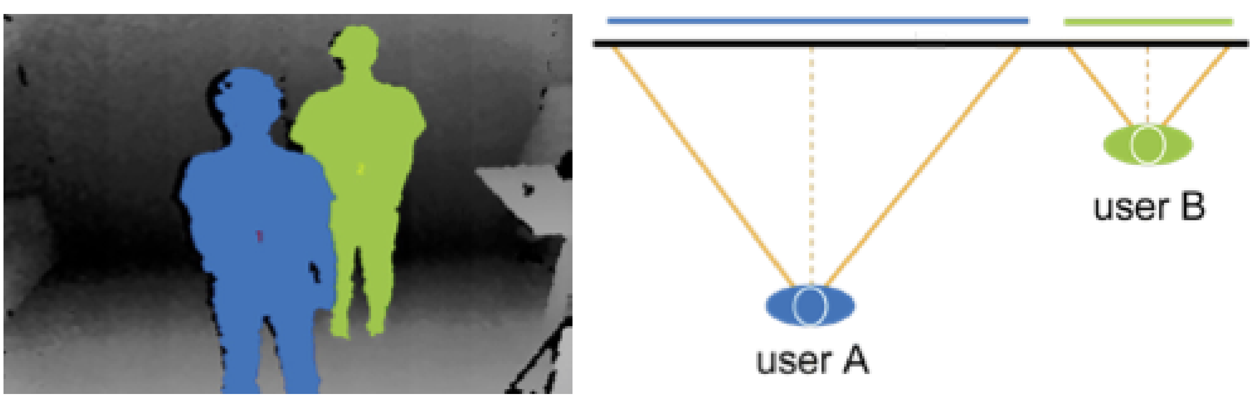

Figure 2.4: "Users in front of the interactive surface are identified and their position tracked using Microsoft Kinect (left). Depending on the distance to the surface the width of their visual field is estimated (right) [1]."

2.3.1 Drawbacks of Local and Global Undo

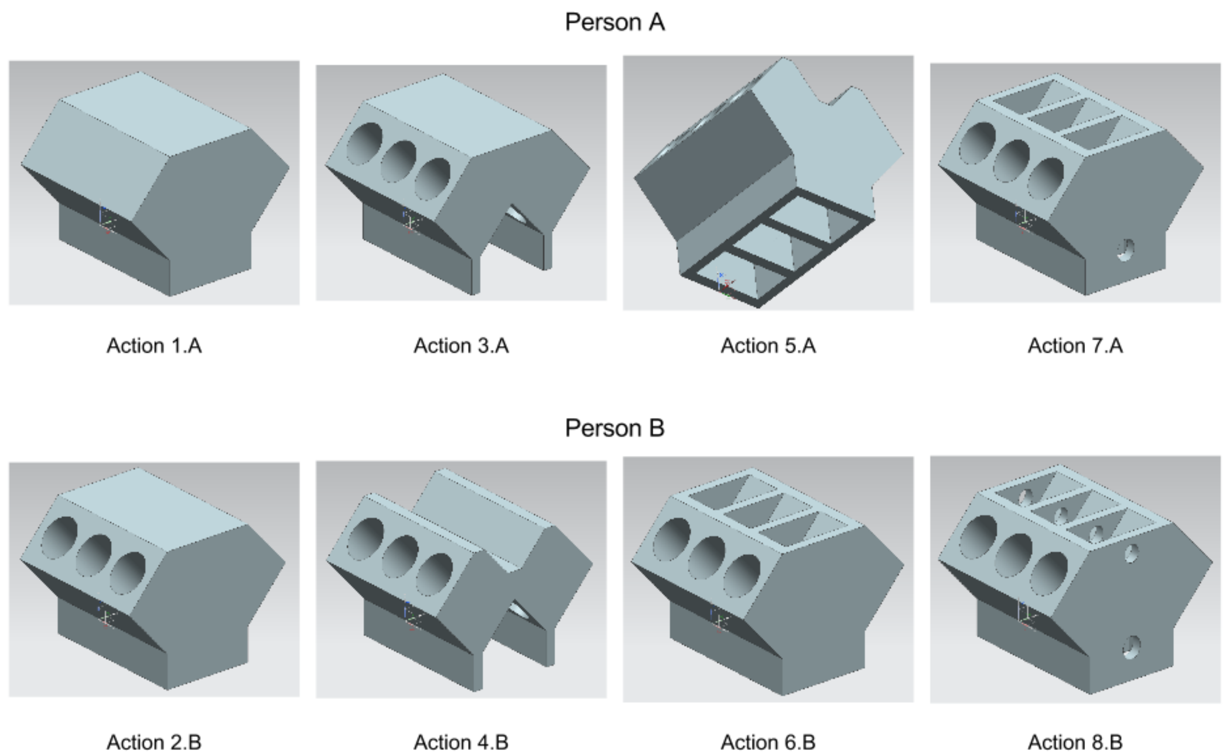

Figure 2.5: Undo Collaboration Scenario

According to Seifried et al., one of the main drawbacks of local undo is that it requires close coordination in order for multiple collaborators to restore their work to a desired previous state [1]. Imagine if two users were collaborating to model a simple engine block. Assume user A performs all the actions in the top row of Figure 2.5 while user B performs all the actions in the bottom row. Also assume they alternate their actions and perform them in numerical order based on the number of the action. If they desired to return to the same state as action 4.B, local undo would require user A to undo actions 7.A and 5.A and user B to undo actions 8.B and 6.B. This required coordination can be error prone and time consuming. In addition, imagine how the complexity could dramatically increase if any of the following scenarios occur:

- user B leaves and is no longer in the model

- additional people had been collaborating in the model and their actions required undoing
- the model was more complex, requiring more careful collaboration to restore the model to a given state

With regional undo, if both users were collaborating, then either user would be able to undo any action taken within that region, regardless of which user performed the action. However, a user's undo actions would only affect the region in which that user is currently working; their undo action would have no effect outside that region.

Global undo also has its own set of drawbacks. An important factor regarding global undo in the study was that users were unaware of the actions of others working on the interactive surface, "even when they were quite close to one another" [1]. Because of this, users were unable to anticipate how their undo actions would affect other people's work because they were often unaware of what others at the whiteboard were doing. In fact, none of the study participants expected their undo actions to have any effect outside of their own work, so long as they did not change what they were focusing on [1]. In addition, Prakash et. al mention that "global undo can often be confusing for users" due, in part, to its "lack of predictability" [8].

To further illustrate the drawbacks of global undo, assume the same situation as above, but now the users are NOT collaborating in the same "region." With global undo, if user A wished to undo action 7.A, but user B had just performed action 8.B, imagine the surprise of both users when user A pressed undo: user A will wonder why action 7.A did not get undone while user B would be confused as to why action 8.B was suddenly undone. Furthermore, imagine a larger model where two users can not even see nor have any knowledge of the other's operations. They may not immediately be aware of what was happening while using undo and may assume a bug in the program and that they have suffered permanent data loss. While a simple example, it illustrates the shortcomings of global undo. As with local undo, as the complexity of the model and the number of users increase, the potential for even more problems arises.

2.3.2 Limitations of the Application of the Interactive Whiteboard Study

While the interactive whiteboard study provides some useful ideas regarding local, regional, and global undo, it is important to note that, while there are some similarities between interactive whiteboards and multi-user CAD, a CAD environment is much more complex. For example, the dependencies that exist between features in a CAD model add an additional level of complexity that the whiteboards do not have. CAD being a 3D workspace while the whiteboards are a 2D workspace also increases that complexity.

2.4 Multi-User CAD

"The need to support collaboration among users for the facilitation of everyday tasks, communication, work, and training has been identified since the early stages of computer usage. This need became more critical when computer networking became available" [9]. CAD tools are no exception to this and the proliferation of tools like Google Docs has helped people see the usefulness of multi-user editing tools. This section provides additional background on and discussion of multi-user CAD.

2.4.1 Goals of Multi-User CAD

The general goal of multi-user CAD is to improve the productivity of engineers and their teams by facilitating better collaboration. This allows companies to bring better products to market faster. Current engineering collaborative tools help enable "better product quality, shorter lead-time, more competitive cost and higher customer satisfaction;" [10] multi-user CAD seeks to contribute to those objectives as well. As Red et al. note, when using CAD tools in industry, "it is now normal for CAx models to be "time period checked out" to several team members in a 24 hour "chase-the-sun" work cycle." However, they have developed multi-user CAD tools with "the intent of collapsing engineering design process times" [11]. One of these tools is NXConnect: a multi-user CAD prototype that allows multiple users to edit the same part or assembly simultaneously [2].

2.4.2 Methods of Developing Multi-User CAD

As Moncur et al. explain, there are two main ways that multi-user CAD tools have been developed, the first of which is to develop an entirely new CAD system from the ground up. This allows the software to be developed with native collaborative features. These tools generally use a central modeling server to execute features and then the clients are primarily responsible for visualizing those features [12]. By developing a tool from the ground up, architectural decisions can be made that will increase the performance, usability, and overall general usefulness of a multi-user CAD system. This architecture can also make it much easier to implement new multi-user functionality. A disadvantage to this approach is that building a new CAD system from the ground up requires a considerable amount of effort due to their extreme complexity.

The second method for developing multi-user CAD is called transparent adaptation. This method uses plugins that provide additional collaborative functionality and capability for existing CAD systems. This allows multi-user functionality to be added to existing tools that users are already familiar with. By utilizing the APIs of the CAD system, changes to the underlying software itself are not needed. However, this method is limited by the functionality that the API exposes [12]. An example of this method is NXConnect, which was built using the NX API [2].

2.4.3 Multi-User CAD UX/UI Considerations

Regardless of the method of implementation, it is critical for the UX/UI of a multi-user CAD tool to allow a target group to "easily access the application and reduce the support cost" [13]. It should "help collaboration take place with one user's awareness of others' activities" [13].

Technical tools such as CAD are already extremely complex and require significant training and experience to become proficient with them; the existence of college-level CAD courses is evidence of this. Developing a multi-user version of these tools has the potential to add even more complexity to these already complex tools. If the desire is to see widespread adoption of these tools in industry, this additional complexity must not negatively affect users' productivity due to their being confusing to use.

In order to bring multi-user CAD to industry, it needs to provide expected behavior for users so that there is less confusion and less of a learning curve. As Red et al. mention, "[c]ompanies will be interested in new collaborative methods that blend transparently within existing CAx tools, rather than complex and additional applications that run outside the mainstream CAx tools" [11]. Thus, the UX/UI of undo must allow it to "blend transparently" into the existing multi-user experience and feel natural to users.

In order to minimize added complexity, the undo mechanism must match the majority of users' expectations as closely as possible. Otherwise, their ability to use the software is diminished, the learning curve is steeper, and the likelihood of continued use of a multi-user CAD tool decreases. This research seeks to draw upon an existing body of knowledge regarding undo mechanisms in multi-user environments and apply it to CAD to provide useful UX/UI recommendations regarding undo.

2.4.4 Existing Research of Undo in Multi-User CAD and Other 3D Modeling Environments

There has been some work done with undo for multi-user CAD and 3D modeling tools. Goal et al. have done work with multi-user AutoCAD [14] while Liu et al. have done work involving a multi-user version of Maya [15]. Cheng et al. have studied consistency and conflict of multi-user undo in CAD as well provided implementations of multi-user undo [16] [17], and finally, both Cheng et al. [18] and French et al. [4] provided implementations of local undo in a multi-user CAD environment. French et al. specifically provided a method for detecting and handling personal (local) undo conflicts in multi-user CAD and their method is discussed further in the Undo In NXConnect Section. However, while several implementations have been provided, little research has been done on how users themselves expect undo to behave.

An additional multi-user CAD tool is called Onshape and is available as a web-based commercial product. It supports undo, but it provides local undo only. However, a user can undo a feature with dependencies that were created by another user. The dependent feature does not regenerate properly, is not displayed in the model, and an error message is shown when the user hovers over the feature in the feature tree [19].

2.5 NXConnect

In this research, NXConnect is used to gather data about user's expectations of undo. According to Red et al., the developers of NXConnect, it is "an add-on to the existing CAD package Siemens NX" and "allows multiple users to access and make changes simultaneously to a single part file." This allows individual users to work independently of one another and to focus on their intended task. However, they will also see updates made to the part file by others in real time [2].

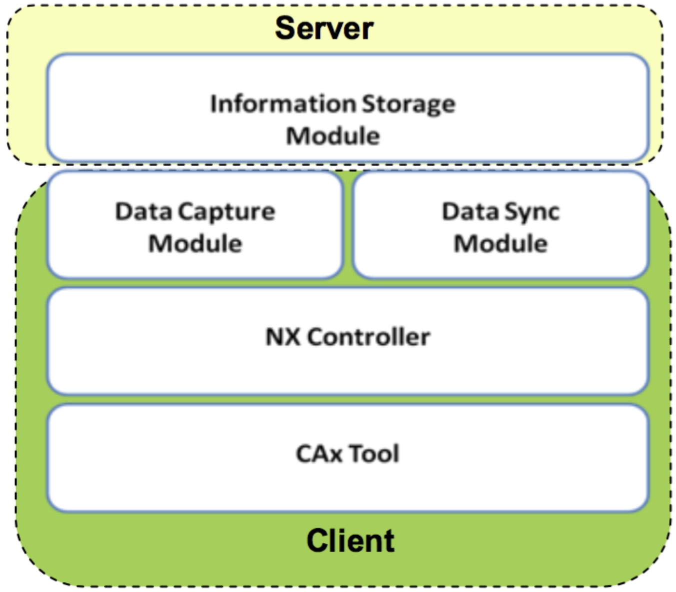

Figure 2.6: Original NXConnect Modules [2]

A common way to describe this to new users is "Google Docs for CAD" due to the familiarity and similarity it has to Google's popular collaborative document editing suite of tools.

NXConnect uses a client-server architecture with a thin server and a strong client. The client is used to generate a full, local copy of the model while the server is responsible to pass the operations of various users to one another as they perform them. Figure 2.6 shows the original modules of NXConnect as well as which modules reside in the server and which reside in the client. The data for each part is broken down by feature, and each feature is decomposed and represented by primitive types such as int, bool, and char. Figure 2.6 illustrates an example of this decomposition [2]. NXConnect has continued to evolve and, while it has been developed to function as a prototype, it has undergone extensive development and provides a wide range of functionality. Because it is built on a well-known CAD system, new users who have experience with NX are already familiar with the interface. This allows the user to focus on using the multi-user capabilities of NXConnect, rather than having to also learn a new CAD interface.

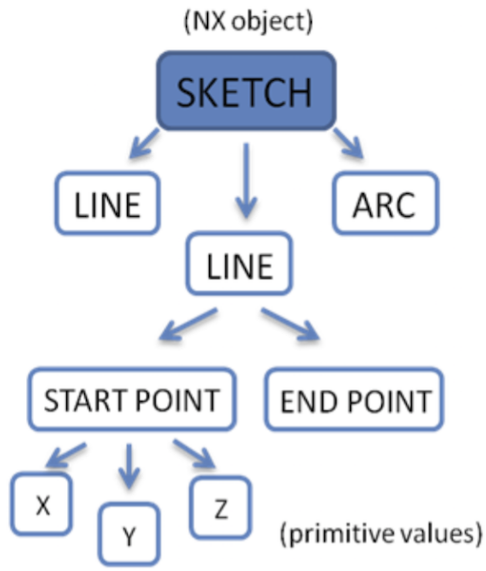

Figure 2.7: NXConnect Primitives [2]

2.5.1 Undo In NXConnect

French et al. developed and implemented a method of undo in NXConnect. Their method allows for local undo, where a user may undo their own actions. A key aspect of their method is that they analyze the current state of the model to deter conflicts and will either allow certain undo actions, disallow them, or prompt the user before applying the undo operation. This is due to the dependencies that features in a CAD model can have, and the fact that one user's local undo actions may affect another user [4]. According to them, conflicts occur when:

1. "the undo does not or cannot provide the expected result due to commands that were performed by other users after the command that is being undone, or"

2. "the undo affects the results of commands that were performed by other users after the command that is being undone." [4].

As a result, "undo can cause unintended consequences for either the local user or for other users." French et al., citing Contero et al., mention two types of conflicts: syntactic and semantic. Syntactic conflicts refer to conflicts that would cause "deficiencies in the mathematical validity of the model" such as invalid CAD features. Semantic conflicts would cause aspects of the model to "fall short of the user's design intent, despite being mathematically valid" [4] [20]. French's undo method protects against syntactic conflicts and some semantic conflicts.

2.6 Current Work

This work seeks to build upon the existing body of research around both multi-user CAD and multi-user undo. Based on this literature review, there is still much research that can be done on undo in multi-user CAD. French et al. mention that undo in multi-user CAD "is an important challenge that needs to be addressed more completely." Their work provides a useful starting point that has proven to be an extremely useful tool in NXConnect and has validated the need for undo functionality in multi-user CAD systems [4]. This research builds upon previous work by gaining a better understanding of how users expect undo to behave. This includes considering local undo as well as other models of undo such as regional and global undo.

CHAPTER 3. METHOD

3.1 Overview

As stated previously, this thesis seeks to better understand what a user expects to happen when they press undo in multi-user CAD. It seeks to build upon the research of others, particularly French et al. However, while French et al. provide a specific implementation of a specific undo method (local undo), this research compliments and adds to that research by attempting to discover, for example, when users expect local undo to be used as well as when they would expect different types of undo such as regional undo. In order to accomplish this, a study of CAD users was performed.

This study was divided into three main activities: the initial expectations survey, the design exercises, and the follow up survey. The initial expectations survey sought to gain a better understanding of the participants' background, their experience with CAD and 3D multiplayer gaming, and their existing expectations of multi-user undo. The design exercises placed participants in simple, yet realistic multi-user CAD collaboration scenarios and then compared their expectations of undo to various undo methods. Their purpose was twofold: simulate realistic collaborative design scenarios and assess users while they were actively using the software. By observing participants in real time, expectations could be most accurately be captured. Finally, the follow up survey had participants watch 8 different videos of 3 people using multi-user CAD in similar scenarios. This provided more controlled scenarios in which specific aspects of undo can be evaluated as well as discovering what factors contribute to a user's expectations.

3.2 Study Participants

Participants for this study must be users of CAD with enough experience to model simple geometry. To fulfill this requirement, study participants were gathered from the mechanical engineering department at Brigham Young University who had at least 1 year of experience using CAD. Many of the participants also had experience using NXConnect either as a developer or a tester. This group is particularly interesting to study due to their familiarity and experience with multi-user CAD. Because of that experience, they have overcome much of the learning curve of working in a multi-user CAD environment and thus they were able to focus more on the design exercises as opposed to the nuances of multi-user CAD in general.

However, it is important to note that with this multi-user CAD experience, these users have begun developing biases and forming opinions about NXConnect. It is important to note this because these biases may affect their perception and opinion of undo behavior. These users are also more familiar with the shortcomings of NXConnect, which may also have an effect. While these things are important to be aware of, the benefits of using this group outweigh the drawbacks. Notwithstanding, future work ought to include broadening the type of participants who participate in the initial expectations survey and the design exercises, including using professional CAD users. Further breakdown of the demographics and experience level of the participants is provided in the Results Chapter.

3.3 Initial Expectations Survey

Prior to beginning the design exercises, the participants were asked to complete two initial surveys: a demographics survey and a survey assessing their initial expectations regarding undo in a multi-user CAD environment. The demographics survey asked about 5 basic demographic items:

- age
- gender
- school major
- year in school
- where the participant identified as their state, country, or region of origin

It then asked them about their experience with CAD and multi-user tools:

- how much experience they had with CAD and how often they used it

- if they had any experience using CAD professionally
- experience with 3D, multiplayer gaming and digital gaming in general
- experience with collaborative editing tools such as Google Docs

The purpose of these surveys was to gain a better understanding of the participants' background and experience. The demographics were strictly informational, but an additional piece of future work worth pursuing would be to study a specific demographic with the intention of better understanding how a person's background may affect their expectations of undo. It is also worth noting that other research has pointed out potential links between multi-user CAD and 3D gaming. Kosmadoudi et al. [21], talking about single-user CAD tools, state that "gaming techniques and mechanisms that may potentially be beneficial to the future development of CAD systems in engineering." In addition, Red et al. [11], while talking about multi-user CAD tools, talk about how many gaming elements "could prove useful in interpreting another user's design intent among several users." Thus, this data may aid in future studies.

The first part of the initial expectations survey proposed 4 hypothetical scenarios in a multi-user CAD environment. For example, the first question was "If you were collaborating with someone in a multi-user CAD environment, if YOU created a sketch, and then THEY extruded that sketch, what would you expect to happen if YOU pressed undo? Why?" This particular scenario was designed to force a distinction between local, regional, and global methods of undo. In addition to the scenario questions, the initial expectations survey asked about what behaviors or actions made the respondent feel as if they were collaborating with other users. Finally, they were directly asked what their expectations were regarding undo in a multi-user CAD environment: "How would you expect undo and redo to perform while collaborating in a multi-user CAD environment?"

3.4 Design Exercises

The design exercises took place in the BYU CADLab using NXConnect and NX 8.0. Participants came and worked in a group of either two or three people and completed one or two different design exercises. Upon completion of these exercises, the participants were stopped and asked about how they would expect undo to behave. Screen and audio recording software were used to capture the participants' actions they performed and any audio that was spoken during the exercise. The audio of the post-exercise interactions between the participant and the researcher were also recorded.

The design exercise portion of the study was deliberately qualitative in nature. It sought to better understand users' expectations regarding undo by allowing participants to reflect on and volunteer their thoughts regarding undo behavior in a realistic design scenario. This is valuable because a more quantifiable experiment involving strictly controlled variables, while perhaps more rigorous, would not have provided the insight needed. This is because controlling the environment too much would lead to an unrealistic scenario that was not representative of actual use cases of multi-user CAD and would have skewed the results. These considerations and rationale are discussed further in the Evolution of the Procedure Section.

3.4.1 Procedure

Participants were seated next to one another during the exercise. Before they began a given exercise, they were provided with a sheet that described the task and provided some images to serve as inspiration for the users' designs. Participants participated in either a team of two or a team of three. The participants who were in teams of two were given two different tasks: designing a simple engine block and designing a piston head. On the other hand, participants who were in a team of three were given only one of the two tasks. For the teams of three, an equal number of total participants participated in each of the two design exercises. Participants were given 10-15 minutes to complete the tasks and the order in which the tasks were completed for the two person teams was determined randomly. During the exercise, the researcher remained in the room with the participants and answered any questions they had. The 10-15 minute buffer was given to allow the researcher flexibility to extend the exercise due to unforeseen events, such as software malfunctions. This helped mitigate the risk of the results being skewed due to external factors.

Upon completion of the exercises, the participants were separated from one another and were asked a series of post assessment questions, one at a time. The order in which they were interviewed was randomly chosen. The researcher would save a copy of the part to the hard drive, open it in single-user NX, and would then ask the participant what they would expect the part to look like if they pressed undo once and why they would expect that to happen. Once they gave their answer, the researcher would simulate the undo action by suppressing, deleting, or editing the feature in question. This returned the part to the undone state the user would expect it to be in. This process was repeated two more times for a total of three simulated undo presses. This was done to make the process feel as realistic as possible. As is discussed in the Conclusions and Future Work Chapter, future work would include developing actual prototypes of various undo methods and testing users expectations against them.

The participants were then asked about which participants they felt they were collaborating with and why. The purpose of this was to gather qualitative feedback about what factors influenced people's sense of collaboration. The results of this question were used to determine the factors presented in the follow up survey. The final questions the participants were asked were the following:

- "Did your feeling of who you were collaborating with change during the exercise?"
- "Did it seem like you were collaborating more or less with them at certain points during the exercise?"
- "How do you think that would affect your expectations regarding undo?"

These questions sought to explore how participants' perceptions regarding collaboration may have changed as the exercise progressed and if those perceptions affected their expectations of undo. This question also gave the researcher the opportunity to further discuss and learn what factors contributed to a participant's sense of collaboration and at what point participants would perhaps expect undo to behave in a different manner. It also provided an opportunity to ask about specific moments in the exercises that may have been of interest because of a unique scenario that the participants were in that may have affected their undo expectations. Finally, it also allowed the researcher to explore hypothetical scenarios in which participants would feel that their expectations of undo would be different.

Piston Head Exercise

The piston head design exercise provided a smaller design space and generally resulted in a more coupled design due to the dependencies between features. In addition, the smaller design space caused participants to work more closely to one another. These factors combined to increase the likelihood that participants would need to collaborate more closely with one another to complete the exercise.

Engine Block Exercise

The engine block design exercise provided a much larger design space in which participants could work. As a result, there was an increased likelihood of a third person working on their own while two other people were collaborating more closely within the model. Notwithstanding these factors, both of these design exercises were deliberately open-ended to better simulate real-world scenarios.

3.4.2 Evolution of the Procedure

The design exercise procedure underwent some iteration as it evolved over the course of this research. It originally consisted of several additional design exercises in addition to a single free-form exercise. These original design exercises consisted of several steps given to each participant to complete. Each step was explicitly laid out and a participant only completed the steps they had been assigned. There were several problems with this approach. First, these exercises were taking a considerable amount of time and several exercises had to be skipped due to the time limitations of the participants. The second and more impactful flaw was that these scripted exercises did not accurately represent a realistic design scenario in which multi-user CAD is used.

These design exercises were originally used to ensure that when participants were asked what would happen when the pressed undo, they would be forced to choose between different undo models. However, this result did not occur because one participant would often end up preventing the other participants from performing their tasks or one participant would finish much faster and have nothing more to do. As a result, this often provided a much less realistic scenario. By providing a more realistic scenario, the results from the design exercises will more closely align with users' expectations.

However, by providing a more free-form exercise, when participants were asked about their expectations regarding undo, their answers often corresponded with two or three undo models. This overlap made it difficult to distinguish with data alone if a participant truly preferred local undo or if it was simply a coincidence that their action also corresponded with a local undo model. In order to avoid this overlap and reduce potential ambiguity between the possible undo models, a follow up survey was administered to all study participants.

3.5 Follow Up Survey

A follow up survey was emailed to study participants after they had participated in the design exercises. This survey presented 8 videos in which 3 users collaborated in NXConnect to perform specific tasks on an engine block. The videos were recorded using the same 3 users and all the scenarios involved similar work. Each of the 3 users' screen captures were played simultaneously side by side. In all but 1 video, the audio of the users was also played back during the video. Indicators were added to the videos so that respondents could tell which user was talking. These videos ranged from 57s to 2 mins 18s in length. Due to the videos' lengths, the overall survey was lengthly and survey fatigue was a concern. "Survey fatigue" is when a respondent has been taking a survey for such a long time that they begin to lose focus and may either abandon the survey or their answers are not as well thought out, which can skew results. In order to combat this, the order of the questions was randomized, so that any effects of survey fatigue would be uniformly distributed.

At the end of a given video, respondents were asked two questions. First, what would they expect to happen if a specific user were to press undo. Anywhere from 3 to 5 different options were presented that corresponded with either local, regional, global, or some other method of undo; respondents were forced to pick a single answer. A "Something else" option was also provided which allowed respondents to type in an expectation that was different from the listed options. In some scenarios, there was overlap between the various types of undo, but efforts were taken to design the scenarios so that they did not cause overlap.

The second question they were asked was to select which factors influenced their expectation of what would happen when a user pressed undo. Based on results gathered from the design exercises, various options were presented and respondents were asked to select all that applied. As with the first question, an additional "other" option was given that allowed the respondent to type in a factor that was not listed. The answers were limited to multiple choice to allow easier coding, comparison, and analysis of these factors.

In addition to the student respondents from the design exercises, the follow up survey was sent to 4 people who currently work in industry and have experience using CAD. It contained all the same questions with 2 additional ones asking how much experience the respondent had using CAD and how often they had used CAD over the past year. The results from these respondents were compared to those of the students to see if any major discrepancies arose or if the students responses generally aligned with those of the professional respondents.

The follow up survey serves two main purposes. The first is to gather more quantifiable data regarding user expectations regarding undo. For example, in certain scenarios, do users prefer local, regional, or global undo? The second purpose is to gain insight into which factors more strongly contribute to when users prefer a shared undo stack over a local undo stack. In order to accomplish these two purposed, it provided a more focused and controlled experiment by building upon the qualitative findings of the design exercises. By using recorded videos of specific scenarios, the rigor and control required for more quantifiable findings was achieved. However, without the more qualitative results of the initial design exercises, it would have been difficult to design the scenarios and questions for the follow up study. Thus, both the qualitative and quantitative aspects of this research proved to be useful tools.

3.6 Method of Results Analysis

While the results themselves are discussed in the Results Chapter, this section discusses the methodology by which the results were analyzed.

Initial Expectations Survey

To analyze the initial expectations survey, participants' answers were coded as expecting either local undo, regional undo, global undo, the software would fail to perform an undo, or they were not sure what to expect. Failing meant that the participants felt the software should not undo anything. Each answer was coded and then the results were compiled together.

Design Exercises

For the design exercises, participants' responses to the post assessment survey were analyzed in a few ways. The participant's responses to the question regarding expected undo behavior were analyzed first. The researcher would watch the captured session videos to determine the final actions that were performed in the model and who performed them by noting the timestamps at which various actions occurred. This was acceptable because the screen recordings were always started together and were in sync with one another. In a few cases, software bugs caused inconsistencies with features being shared between participants or user's work would be lost. In these cases, participants were asked to assume that their work had not been lost and to base their answers regarding undone actions on that. Then, each answer a participant gave was analyzed to see if a distinction could be made between a local undo stack or a shared undo stack. Note that in many cases, a distinction could not be made. For example, assume user A and B were the only two users in a part and user A created a sketch followed by user B extruding that sketch. If user B had answered that they would undo their action (the extruding of the sketch), this result would be inconclusive because their answer would be the same regardless of whether a local or a shared undo stack was being used. Thus, these answers were marked as inconclusive as they did not provide sufficient insight into a participant's expectations nor their preference of one undo method over another. This is discussed further in the Results Chapter, but even with the inconclusive results that were discarded, all participants indicated that their expectations were consistent for all three undo actions in a given scenario. Thus, the omission of the inconclusive results did not have an impact on the overall results and conclusions of the design exercises.

Based on this analysis, the action was then assigned an undo stack preference of either "Local" or "Shared" while the inconclusive actions were not assigned an undo stack preference. Here, the term "undo stack preference" is used to indicate whether a participant's expectations indicated they would expect a shared undo stack or a local undo stack in a given exercise. Next, for each participant and each design exercise, all of the actions were analyzed to see if any of the participant's actions had different undo stack preferences within a single exercise. If they were the same for all actions, that scenario for that participant was assigned an undo stack preference of either "Local" or "Shared." For the two person teams, each individual scenario was analyzed for each person. If the participant had the same undo stack preference for both scenarios, they were assigned that same preference as their overall undo stack preference. If they had two different preferences for each scenario, they were assigned an overall undo stack preference of "Divided." Because the three person teams only completed one design exercise, their undo stack preference for that one exercise also represented their overall undo stack preference.

Finally, participants' responses to the final questions regarding levels of collaboration were used to determine the factors that were given as possible answers in the follow up survey. The participants' answers to the question of why they felt they were collaborating with a given user were complied together. Because these answers were the result of a free form discussion, a researcher coded the answers into 17 different categories. 7 of the most common answers were included in the follow up survey as possible factors that could contribute to a user's undo expectations.

Follow Up Survey

The follow up survey results were analyzed scenario by scenario. For scenarios 1-6, each selected action within the first question was coded as a local, regional, global, or other undo method. If a respondent answered "Something else," their free form answer was either coded into one of the existing methods or an additional method was added. For example, some respondents indicated that they would want the operation to fail. Rather than coding these responses as "Other", they were coded as "Fail." These results were then complied and charted. The results of the second question were tabulated and sorted by how many users selected a given factor.

Scenarios 7 and 8 were slightly different, though the process was similar. Their choices for the first question included an action where the undo action would fail and another action where the user had to confirm their undo action. As such, the answers to these questions were not coded and were reported as written. This is due to the fact that these scenarios had a different purpose and focus than the other 6. This is discussed further in later chapters.

If the results of the follow up survey provide strong evidence to support dynamically switching between different undo modes, an equation will attempt to be derived that governs when that switch should occur.

CHAPTER 4. RESULTS

4.1 Participants

This section presents and discusses information about those who participated in all three parts of the study. It presents their demographics and their experience with CAD, mutliplayer 3D gaming, and digital gaming in general as well a general discussion of the participants.

4.1.1 Demographics

A total of 20 participants participated in the study of which 90% were male and 10% were female. They were all mechanical engineering students who were juniors or higher in school. A detailed breakdown of the participants' year in school is shown in Figure 4.1. Their average age was 25.6 years with a standard deviation of 2.2 years.

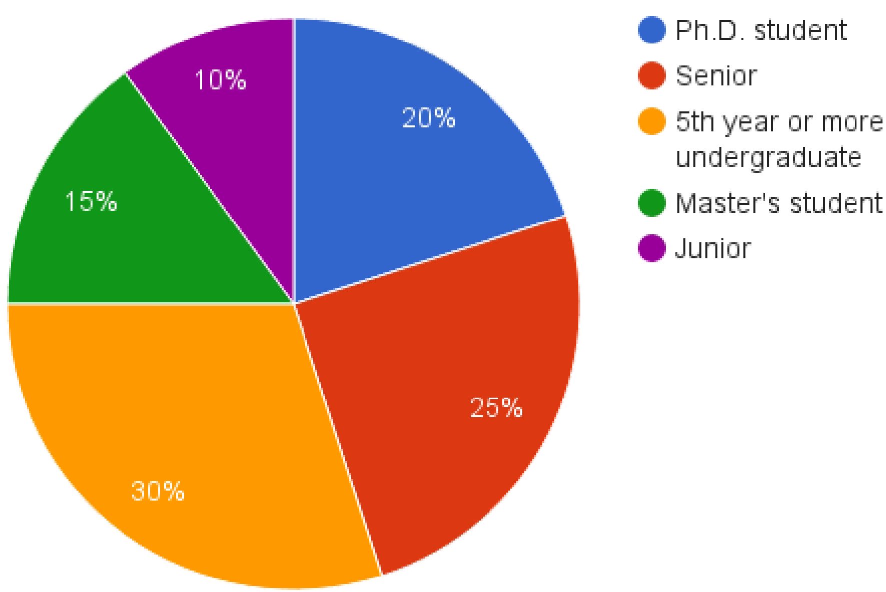

Figure 4.1: Year in School

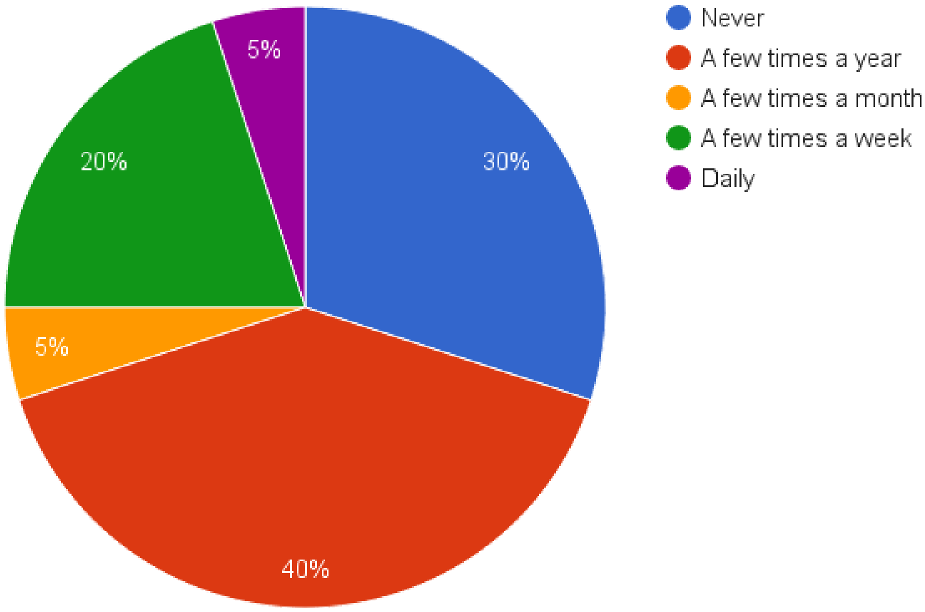

Figure 4.2: 3D Game Experience Over the Past Year. On average, how often have you played a realtime, 3D, multiplayer game (such as Halo, Starcraft, League of Legends, Minecraft, World of Warcraft, etc.) over the past year?

4.1.2 Experience

In addition to demographics, the participants were asked about their past experience with CAD, digital games, and other collaborative editing tools such as Google Docs. Only 1 participant said they had 1-2 years of experience using CAD tools while the rest stated they had more than 2 years of experience. Regarding that experience, 50% of participants had used CAD professionally (not including paid academic research) with 50% having never used CAD professionally. In addition, over the past year, 25% of participants reported that they had used CAD daily while 55% reported using it a few times a week. The remaining 20% reported that they had used CAD a few times a month over the past year.

Regarding digital games, 50% of participants said they had more than 5 years of experience with real-time, 3D, multiplayer gaming (such as Halo, Starcraft, League of Legends, Minecraft, World of Warcraft, etc.), while 10% had no experience with those types of games. The remaining 40% said they had some experience, though less than 5 years. The remaining answers to the gaming questions are shown in Figures 4.2, 4.3, and 4.4.

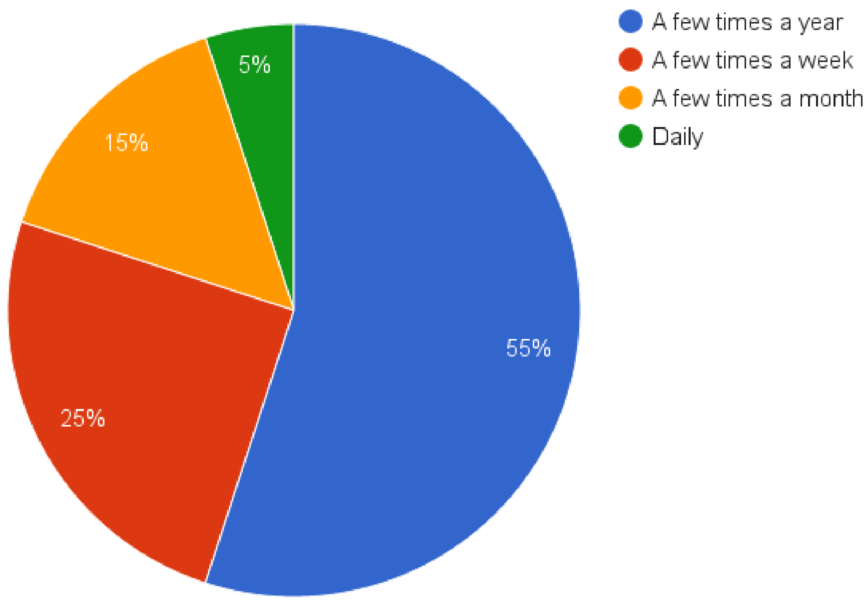

Figure 4.3: General Game Experience Over the Past Year. On average, how often have you played any sort of digital game over the past year?

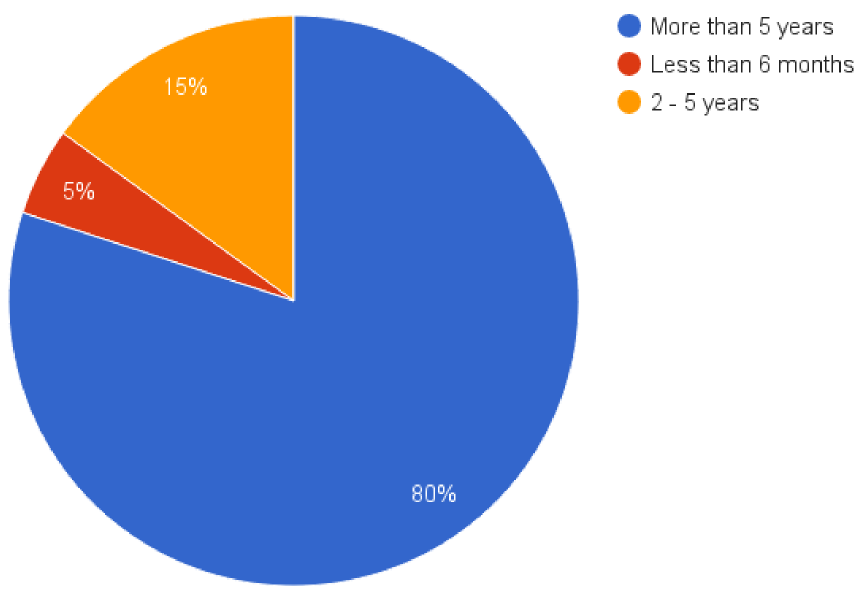

Figure 4.4: General Game Experience. How long have you had experience with any sort of digital game in general?

Finally, participants were asked about their experience using Google Docs or other collaborative document editing software. 60% of participants reported having 2-5 years of experience with Google Docs or other collaborative document editing software while the remaining 40% said they had more than 5 years of experience with such tools. Regarding how frequently they used these tools over the past year, 20% reported daily use, 45% reported using them a few times a week, 25% reported using them a few times a month, 5% reported using them a few times a year, and 5% reported that they had not used these tools at all over the past year. When asked about other collaborative editing tools they had used in the past, they included tools such as Lucidchart, NXConnect, ShareLatex, and Microsoft Office 365.

4.1.3 Discussion of Participants

Based on these results, these participants were good candidates for this study because they understand how CAD software works and were able to use it effectively. Their experience level ensured that the exercise was spent modeling instead of struggling to perform basic operations in CAD. This, combined with the fact that they are all mechanical engineering majors, means they have a high likelihood of using CAD tools at some point in their professional careers as well as having a high likelihood of using multi-user CAD tools when they become more widely used in industry. Therefore, it is important, to understand their expectations because they represent the future users of multi-user CAD.

It is also interesting to note that all of them had significant experience (2 or more years) with collaborative editing tools such as Google Docs. In addition, 90% had at least some experience with 3D multiplayer gaming and 70% of participants reported having played a multiplayer, 3D game at least a few times a year last year. They represent a generation of users who have gone through most if not all of their college careers already familiar with a multi-user collaborative paradigm. Many have also grown up using 3D environments in which they interact, are aware of, and must collaborate with other users to achieve some objective, not unlike CAD in many ways. It is important to recognize this experience because it means their expectations may be different than other users who do not have similar experiences, in particular users who are older or perhaps from different cultures or parts of the world. That being said, they still represent future users of multi-user CAD, and thus their unique experience and background ought to be taken into account.

With this in mind, there were two weaknesses of this group of participants. First, they were novice users with limited professional engineering and professional CAD experience. Second, they were a fairly homogeneous group that may or may not align closely, from a demographic standpoint, with engineers as a whole. They were all from the same university, were all from the US, were around the same age, and had similar levels of experience using CAD, collaborative tools, and multiplayer 3D gaming. In addition, this group was not compared to demographic data of CAD users generally.

4.2 Initial Expectations Survey Results

The first question of the initial expectations survey was: "If you were collaborating with someone in a multi-user CAD environment, if YOU created a sketch, and then THEY extruded that sketch, what would you expect to happen if YOU pressed undo? Why?" If a user expected the other users' extrusion to be undone, this corresponded with an expectation of a regional undo model. If they answered that they wanted their own action to be undone, this corresponded with a local undo model. Two other answers that were given were that they expected the undo attempt to fail and for nothing to be undone or that they were unsure what should happen. The breakdown of these answers is seen in Figure 4.5. Nearly half of the participants expected regional undo while almost a third expected local undo.

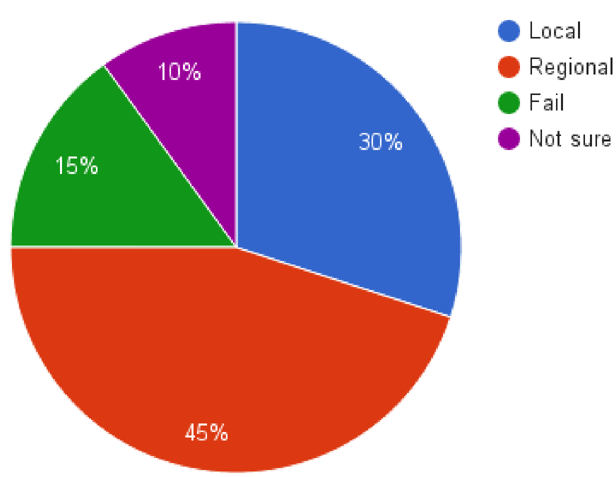

Figure 4.5: Initial Expectations Survey Question 1 Answers

The next two questions were: “If you were working with someone in a multi-user CAD environment, but you were not collaborating, if THEY created a sketch, and then THEY extruded that sketch, and YOU created a different sketch afterwards, what would you expect to happen if YOU pressed undo? Why?” and “If you were collaborating with someone in a multi-user CAD environment, if YOU created a sketch, and then THEY extruded that sketch, what would you expect to happen if THEY pressed undo? Why?” For both of these questions, 100% of the answers were consistent with local undo, which would be that the user’s last sketch would be undone in the first scenario and that the other user’s extrusion would be undone in the second scenario.

The fourth question was: “If you were working with someone in a multi-user CAD environment, but you were not collaborating, if THEY created a sketch, and then THEY extruded that sketch, and YOU created a different sketch afterwards, what would you expect to happen if THEY pressed undo? Why?” The distinction in this question is between local and global undo models. As seen in Figure 4.6, a large majority of users (75%) expected local undo in this scenario compared with only 20% of users who expected global undo.

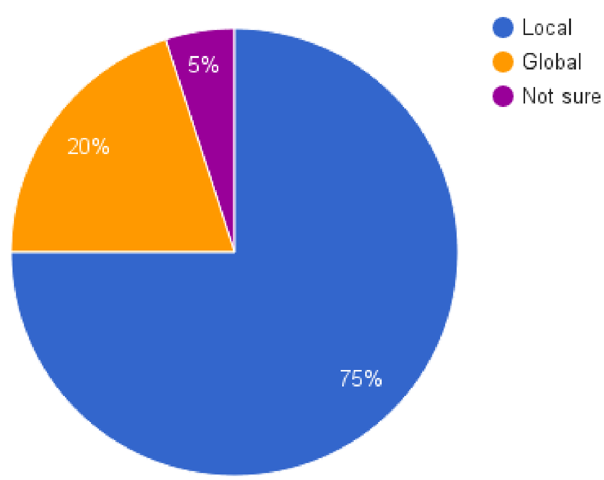

Figure 4.6: Initial Expectations Survey Question 4 Answers

The final two questions were qualitative in nature: “What behaviors or actions (from you or your collaborators) would make you feel that you are collaborating with someone in a multi-user CAD environment?” and “How would you expect undo and redo to perform while collaborating in a multi-user CAD environment?" As discussed previously, the results of these questions helped aid in the creation of the follow up survey.

4.3 Design Exercise Results

Of the 20 participants, 8 participated on a two person team and 12 participated on a three person team. Of the three person teams, 6 participants performed the engine block design exercise and 6 performed the piston head design exercise, or 2 teams for each exercise.

Data regarding whether participants preferred a local undo stack, a shared undo stack, or whether they had different preferences between the two scenarios is shown in Figures 4.7, 4.8, and 4.9. Out of all the participants, 70% preferred a local undo stack in both scenarios while 15% of all participants preferred a shared undo stack in both scenarios. The remaining 15% were divided in that they preferred a shared undo stack during one exercise and a local undo stack for the other exercise.

Of the 8 participants who were on a two person team, 25% preferred local undo in both scenarios, 37.5% preferred shared undo in both scenarios, and 37.5% were divided. Of the 12 participants who were on a three person team, 100% of participants preferred local undo. It is noted that these participants only participated in one of the design exercises.

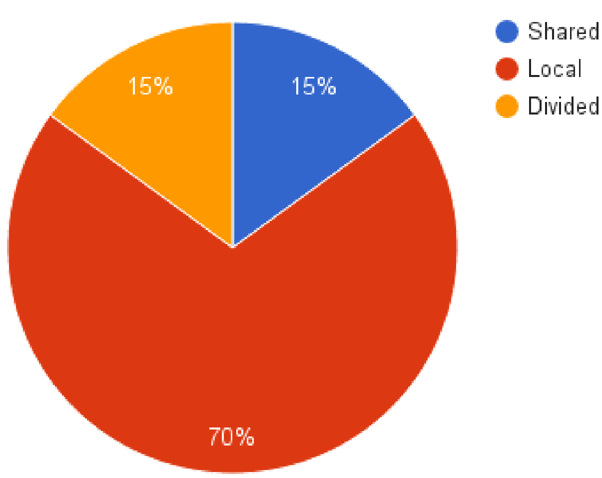

Figure 4.7: Undo Stack Preference - All Participants

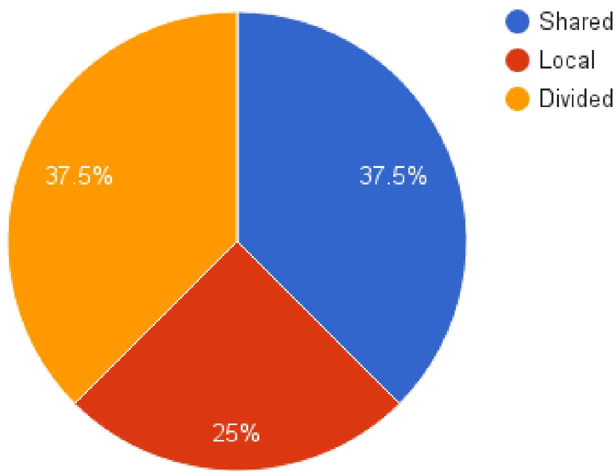

Figure 4.8: Undo Stack Preference - 2 Person Teams

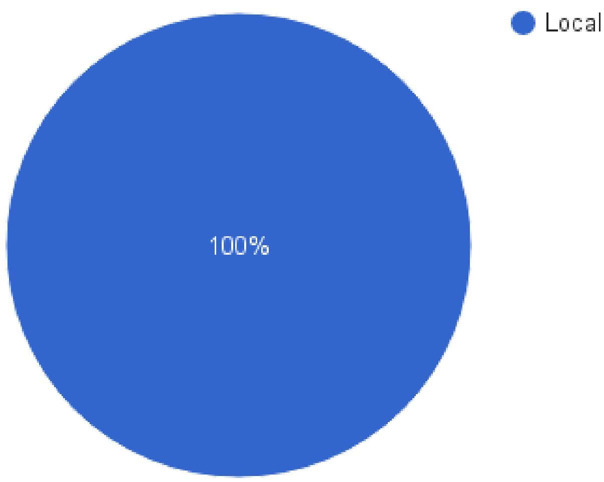

Figure 4.9: Undo Stack Preference - 3 Person Teams

A few additional points are also worth noting. First, for one participant during one of the design exercises, none of their 3 undo actions could be distinguished between a shared and a local undo stack and thus their results were inconclusive for that scenario. However, this participant was on a two person team and participated in a second design scenario which did produce a conclusive result of a local undo stack. Out of all 20 participants, this was the only scenario in which this occurred. Also worth noting is that when asked why they chose their particular actions to undo, the participants mentioned it was because it was the last action they had performed, independent of anyone else's actions. Thus, even though that single result was not used, they indicated that they

Table 4.1: Common Reasons Given for Selecting an Undo Action

Category of answer	# of users
Verbal communication with other users	9
Discussing the work they were performing	9
Discussing and making design decisions	8
Working on the same part	7
Able to see other user's actions	6
Spent time initial planning with other users	6
Had a shared design intent with other users	5
Were sitting next to other users	4
They were building on dependent features	4
Working in close proximity to other users within the model	3

would have preferred a local undo stack. Second, 17 of the 20 participants had at least one scenario in which 2 or even 3 of their actions were distinguishable between a local and a shared undo stack preference. However, for these 17 participants, the undo stack preference was the same for all of their distinguishable actions within the same scenario. This suggests that while expressing their preferences for their three undo actions, their expected undo method did not change from action to action even if it did change from scenario to scenario, as it did for 3 of the 17 participants with multiple distinguishable actions.

In addition to these results, the participants were asked what contributed to their feeling of collaboration with other participants. The most common answers are provided in Table 4.1. Note that these answers were volunteered by participants and they were not pressed to give a certain number of answers. With a few exceptions, each of these answers was included in applicable scenarios in the follow up survey. "Spent time initially planning with other users" was not included in the follow up survey because the videos did not show any extensive amount of initial planning time. The answer "were sitting next to other users" was not included either. This was because even though respondents were told the users in the videos were seated next to one another, there was nothing to clearly indicate this during the videos as only the users' screens and audio were recorded.

4.3.1 Discussion of Design Exercise Results

The results of the design exercises provide valuable information regarding users' expectations: they provide feedback and insight into those expectations in the moment that the user is performing the action. While they are immersed in the environment and actually using the software, this is when understanding their expectations is most critical. From the results gathered, there are several interesting points worth discussing.

With 70% of participants always preferring a local undo stack and an additional 15% preferring it in at least 1 exercise, there is strong evidence to suggest that in multi-user CAD users generally prefer local undo to be used. A common theme mentioned by users was that they would not want to unexpectedly undo another user's actions. This would lead to confusion for both users: the user who issued the undo command may not see ANY action be undone and may question if the software even received the command. Meanwhile, the user whose action DID get undone would be confused as to why their previous work is now gone. This scenario decreases the usefulness of multi-user CAD because users will stop using undo if they are unsure about how it will perform in a given scenario.

Another interesting thing to note is that for the two person design exercises, users were much more likely to be both divided and prefer a shared undo stack as evidenced by the 75% of participants in this state. This means that 75% preferred in at least 1 scenario that a shared undo stack be used. In contrast, all 100% of the participants on a three person team preferred local undo.

Due to the small sample size and the between subjects design of the three person teams, these results merit further research to see if the trend holds true for a larger sample size of users. However, participants did provide some feedback that provided a possible insight as to why 100% preferred local undo in these instances. Participants on the three user teams often reported that it was difficult or impossible to keep track of who was performing which action because they had to keep track of the actions of two people. Contrast this with only needing to keep track of one other person on the two person teams. In addition, on a two person team, a user knows exactly who performed a given action because there is only one other possible person. However, on a three person team, it may not be immediately apparent who performed an action, because there are two possibilities. This understanding of who performed what action is critical if a user is to prefer a shared undo stack. However, as will be discussed further, it is not the only requirement.

NXConnect sometimes exhibited bugs during the study, which may have skewed the users' preferences. While this is unavoidable because almost all software has bugs, it is important to note. NXConnect generally operated normally, but there were a handful of incidents that required participants to deviate from the normal actions they would have taken had those bugs not been present. In the follow up interview with those participants, it did not appear that those bugs affected their perceptions regarding undo, and thus those bugs did not seem to have affected the study results in any way. Future researchers ought to keep this in mind, and future work could be performed using a more stable prototype to eliminate any doubt as to whether software issues affected the participants' expectations.

In addition, during post exercise discussions, several users mentioned that during brainstorming or design review activities, they would be more likely to want shared undo due to the iterative nature of a brainstorming session or the shared design intent and more formal structure of a design review. However, when the task was to simply create assigned geometry, users mentioned wanting to generally have local undo instead. In the future, it would be worthwhile to study how undo expectations are affected by the stated purpose of the collaboration.

Other feedback from users included the idea of dedicated undo commands: one command that always performs a local undo and another command that always performs a regional undo. This design was proposed by several users independent of one another. In addition, several users mentioned the desire to be warned about either why an undo action failed, that they were about to undo an action with a dependency, or that they were about to undo a user's action.

Finally, it is important to note that these results do not indicate that users exclusively prefer a shared undo stack versus a local undo stack. In fact, the 15% participants who were divided and preferred a local undo stack in one scenario and a shared undo stack in a different scenario are perfect examples of how users' expectations are influenced by a variety of factors and can be different from scenario to scenario. Nor do these results indicate objection to shared undo. These numbers simply indicate that a majority of users in a majority of scenarios prefer a local undo stack. In addition, 30% of participants indicated in at least one scenario that they would prefer a shared undo stack, thus providing evidence that a local undo stack is not always the behavior that users expect in a multi-user CAD environment.

4.4 Follow Up Survey Results

All 20 of the 20 design exercise participants responded to the follow up survey. In addition, 4 respondents who were professionals working in industry also responded to the survey. Of these professionals, 25% had 1 year or less of experience using CAD professionally, 50% had 5 to 10 years of experience, while 25% had 10+ years of experience. In addition, 75% of the professional respondents said they had used CAD a few times a week over the past year, while 25% said they had not used CAD at all over the past year. The professionals' responses were not combined with those of the study participants and are presented separately in the tables and figures below; additional discussion of the professionals' results is provided in the Discussion of Industry Professionals' Responses Section.

Regarding the length of the survey, removing outliers of more than 1 hour, it took respondents an average of 31 min 57 s to complete the survey with a standard deviation of 13 mins 11 s. Outliers of 1 hour or more were removed because it is assumed that these respondents forgot to submit the survey until a later time or paused the survey and resumed it later.

4.4.1 Scenario 1

The results for scenario 1 are shown in Figures 4.10 and 4.11 and Table 4.2. Some additional points are worth noting:

- 5% of respondents would want the undo action to simply fail and do nothing
- 1 respondent would want to allow the user to choose between undoing their action and the action of user 2; this response was counted as "other"
- 1 respondent would want to "undo the edit of the cylinder after notification to the user;" this response was counted as a regional undo answer
- 3 respondents provided other answers for factors that influenced their decision:
  - "As an outside observer, I would expect that pressing 'undo' would undo the last action performed by anyone in the part. If I were a user, I would instead expect that each user will only be able to 'undo' their own last action in the part."

– "User 1 needed to be aware that a change was made that was related to what he was working on."

– "That was the last thing he did."

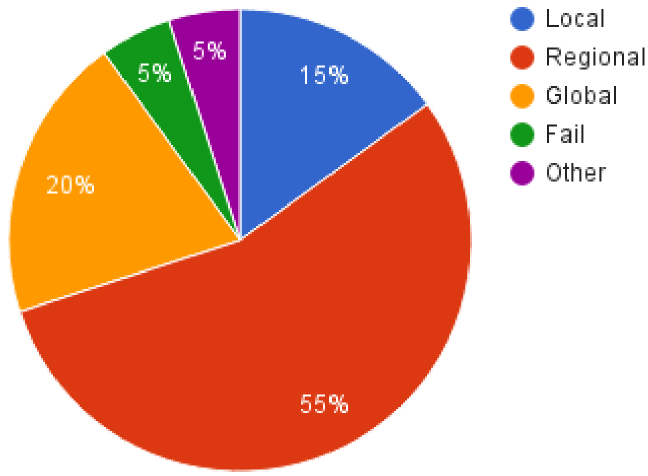

Figure 4.10: Scenario 1 Undo Method Preference

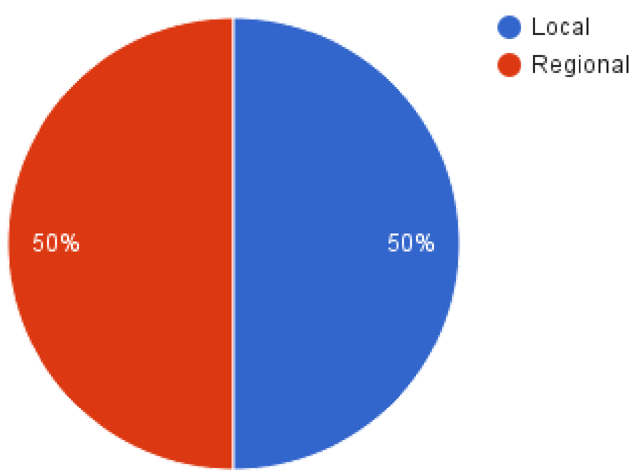

Figure 4.11: Scenario 1 Undo Method Preference - Professionals

In addition to these results, Table 4.3 shows the responses to the second question for only those users whose first answer corresponded with a regional undo model.

Table 4.2: Scenario 1 Undo Factors

Factor	% of users	% of pro users
Users 1 and 2 were working on the same feature at the same time	65%	25%
There was verbal communication between users 1 and 2	50%	25%
You felt users 1 and 2 had a shared design intent with one another	50%	25%
Users 1 and 2 were discussing the work they were performing	45%	25%
Users 1 and 2 were discussing design decisions	45%	25%
You felt users 1 and 2 were working in close proximity	45%	50%
User 1 was able to see user 2's actions	30%	25%
The action you would want to be undone was the last action performed by anyone in the part	30%	0%
The users were all working in the same part	30%	25%
Other	15%	50%
User 1 was able to see user 3's actions	0%	25%
You felt users 1 and 2 DID NOT have a shared design intent with one another	0%	0%

Table 4.3: Scenario 1 Undo Factors - Regional Undo Respondents Only

Factor	% of users	% of pro users
There was verbal communication between users 1 and 2	100%	50%
Users 1 and 2 were discussing the work they were performing	92%	50%
Users 1 and 2 were discussing design decisions	92%	50%
Users 1 and 2 were working on the same feature at the same time	92%	50%
You felt users 1 and 2 had a shared design intent with one another	85%	50%
You felt users 1 and 2 were working in close proximity	77%	100%
User 1 was able to see user 2's actions	62%	50%
The users were all working in the same part	15%	50%
The action you would want to be undone was the last action performed by anyone in the part	8%	0%
User 1 was able to see user 3's actions	0%	50%
You felt users 1 and 2 DID NOT have a shared design intent with one another	0%	0%
Other	0%	0%

Discussion of Scenario 1

The primary purpose of scenario 1 was to force respondents to make a distinction between local, regional, and global undo. The scenario was designed such that user 3 performed the last global action in the part while user 2 performed the last action between users 1 and 2. In addition, users 1 and 2 were working together on the length of the cylinders at the same time and were talking about both the actions they were taking and their design intent. Meanwhile, user 3 did not communicate with either of them and did their own independent work in a different part of the model. The respondent was asked what they would expect to happen if user 1 pressed undo.

This scenario provided the strongest evidence that global undo was not a desired undo method for most users. This is evidenced by the fact that only 20% of respondents chose an action to undo that was consistent with global undo.

This scenario also shows that a majority of respondents (55%) feel that a shared undo stack is the expected behavior in at least some scenarios and that, more specifically, regional undo is preferable to other undo methods. In addition, it provided extremely useful insight into why respondents felt that regional undo was the expected undo model. When considering only those respondents whose answer represented a regional undo method, 100% said that verbal communication between users 1 and 2 was a factor that influenced their expectations regarding regional undo. However, it was not the verbal communication alone that contributed. 92% of those respondents mentioned the fact that the users were discussing the work they were doing and 92% cited the fact that they were also discussing design decisions as a factor. Thus, it is not simply the verbal communication itself, but it is also the content of that communication that influences whether a user expects regional undo or not. Other critical factors include:

- working on the same feature at the same time (92%)
- the respondent feeling the collaborating users had a shared design intent (85%)
- the respondent feeling that the users were working in close proximity (77%)
- the fact that user 1 was able to see user 2's actions (62%)

Interestingly, the fact that user 1 was able to see user 2's actions was not cited as frequently as other factors. However, it is perhaps implied that if the users are working on the same part at the same time, they are also able to see the other user's actions and this may have factored in to respondents' answers. Regardless, all of these factors had a significant impact (greater than 65% of all users) on a user's expectations regarding whether they expect regional undo or not.

A related observation is that respondents did not expect a shared undo stack simply because they could see the actions of another user. This was also observed in the other scenarios. This is evidenced by the fact that the scenarios were all designed such that all the users were generally able to see the actions of all other users. Despite this, the majority of respondents expected local undo, except in those scenarios where other criteria were also met. Both of these findings regarding the ability to see other users' actions stand in contrast to the findings of the interactive whiteboard study in which users expected a shared undo stack in 86% of scenarios in which they were able to see another user's work [1].

4.4.2 Scenario 2

The results for scenario 2 are shown in Figures 4.12 and 4.13 and Table 4.4. 5% of respondents would want the undo action to simply fail and do nothing. In addition, 5 respondents answered "Other" for the second question. Their answers are provided below:

- "It was the last action taken by User 1."
- "Since I observed the video as an outside observer, and could view all three of the screens at once, I would expect that if anyone pressed "undo" it would undo the last thing anyone did in the part. However, if I were a user, I would expect that each user could only undo their own actions (and not the actions of other users)."
- "That was the last action that User 1 performed."
- "that was the last thing they did."
- "User 1's actions had no effect on any other actions."

Discussion of Scenario 2

This scenario had the following purposes:

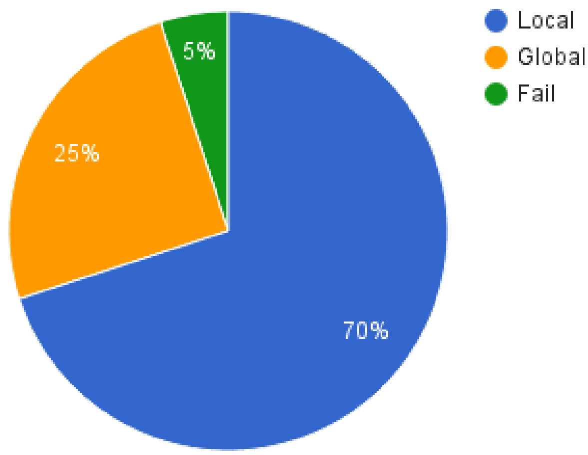

Figure 4.12: Scenario 2 Undo Method Preference

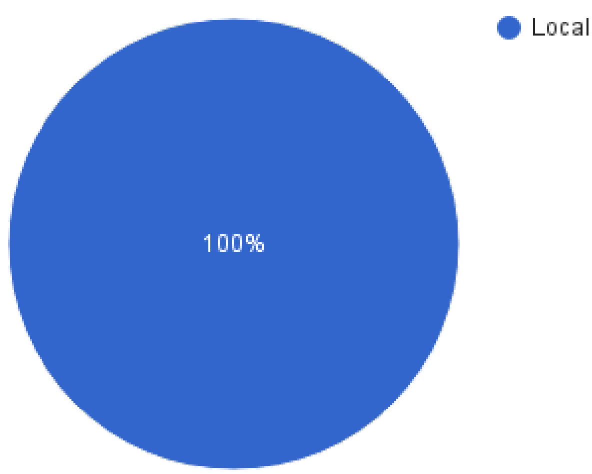

Figure 4.13: Scenario 2 Undo Method Preference - Professionals

- provide an additional scenario that forces a distinction between global undo and a different undo model
- show how being able to view another user's actions influences undo expectations
- explore how verbal communication that did not pertain to the work at all affects expectations
- explore how working on the same feature but at a different time than another user affects expectations

Table 4.4: Scenario 2 Undo Factors

Factor	% of users	% of pro users
Users 1 and 2 were NOT discussing the work they were performing	50%	25%
Users 1 and 2 were NOT discussing design decisions	45%	25%
The action you would want to be undone was the last action performed by anyone in the part	25%	0%
The users were all working in the same part	25%	25%
Other	25%	50%
You felt users 1 and 2 were NOT working in close proximity	15%	50%
You felt users 1 and 2 did NOT have a shared design intent with one another	15%	0%
Users 1 and 2 edited the same feature	10%	0%
User 1 was able to see user 2's actions	5%	25%
User 1 was able to see user 3's actions	5%	25%
You felt users 1 and 2 were working in close proximity	5%	0%
You felt users 1 and 2 had a shared design intent with one another	5%	0%
There was verbal communication between users 1 and 2	0%	25%

In scenario 2, users 1 and 2 are not talking about the work they are doing but rather where they are going to eat lunch. They are not working on related features at the same time, but user 1 creates the cylinders in the engine block and user 2 edits them about 1 minute later. User 3 does not communicate with either user 1 or user 2 and works on features that are independent of user 1 and 2's work. The respondent was then asked what they would expect to happen if user 1 pressed undo.

As with scenario 1, very few respondents (25%) preferred true global undo, while a large majority (70%) expected local undo and 5% expected the action to fail. In addition, even though this scenario featured verbal communication and two users that worked on the same feature, that verbal communication was about unrelated things, and user 2 edited user 1's feature some time after it had been created. By then, user 2 was no longer focused on that feature and was now working on something else. This shows how both of these factors together are not enough to cause a user to expect a shared undo stack.

4.4.3 Scenario 3

The results for scenario 3 are shown in Figures 4.14 and 4.15 and Table 4.5. 2 respondents answered “Other” to the second question; their answers were:

- “That was the last thing they did.”
- “That was the last action that User 3 performed”

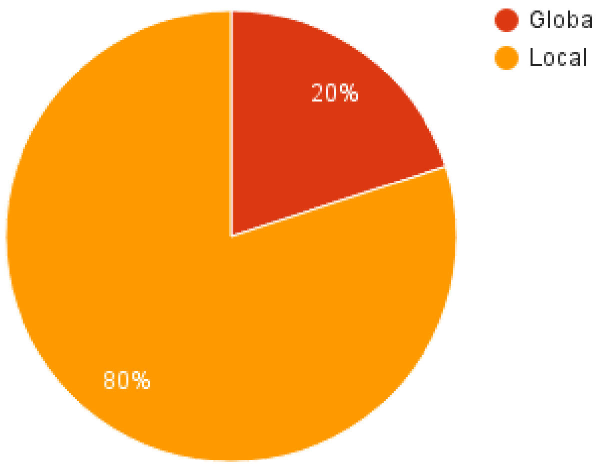

Figure 4.14: Scenario 3 Undo Method Preference

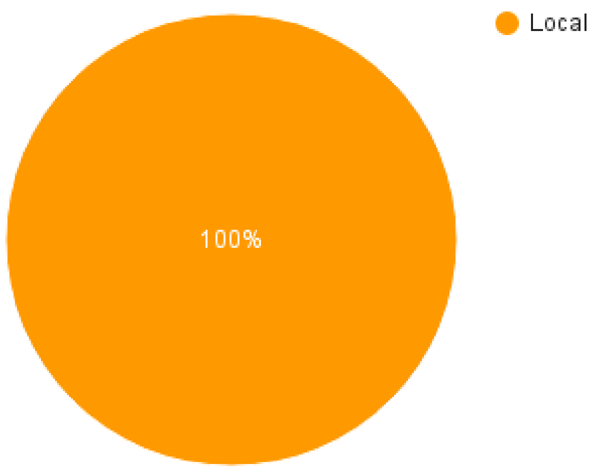

Figure 4.15: Scenario 3 Undo Method Preference - Professionals

Table 4.5: Scenario 3 Undo Factors

Factor	% of users	% of pro users
You felt user 3 was working independently from users 1 and 2	65%	0%
User 3 was NOT discussing design decisions with users 1 and 2	60%	0%
User 3 was NOT discussing the work they were performing with users 1 and 2	55%	0%
The action you would want to be undone was the last action performed by anyone in the part	30%	0%
You felt user 3 did NOT have a shared design intent with users 1 and 2	30%	0%
The users were all working in the same part	20%	0%
You felt user 3 was NOT working in close proximity to users 1 and 2	20%	0%
Other	10%	75%
User 3 was able to see user 1's actions	5%	0%
User 3 was able to see user 2's actions	5%	25%
You felt user 3 had a shared design intent with users 1 and 2	5%	0%
You felt user 3 was working in close proximity to users 1 and 2	5%	0%

Discussion of Scenario 3

This scenario was very similar to scenario 1 with the major difference being that user 3 did NOT perform the last action, and the respondent was asked what they would expect to happen if user 3 pressed undo. Users 1 and 2 were working together on the cylinders, as well as communicating what they are working on and discussing design decisions. User 2 made a similar edit to what made in scenario 1. The respondent was then asked what they would expect to happen if user 3 pressed undo.

This scenario provided another opportunity for distinction between global undo and other models of undo with a few differences in the scenario. Again, respondents showed that they did not expect global undo with 80% preferring local undo versus the 20% who preferred global undo.

In addition to this further evidence against global undo, the answers to the factors question for this scenario are worth discussing. For this question, 65% of respondents said that the fact that user 3 was working independently from users 1 and 2 played a role in their undo decision. This value increased to 79% when only users whose expectations aligned with local undo were considered. This seems intuitive and shows how a feeling of working independently from other users is a strong indicator of a preference towards local undo. The lack of communication about the work being performed also played a role with respondents who expected local undo, citing the fact that user 3 was not discussing design decisions with the other users (63%) nor were they discussing the work they were performing (63%).

4.4.4 Scenarios 4, 5 and 6

In scenarios 1, 2, and 3, user 3 was always working independently of users 1 and 2, who were working together. In addition, user 3 did not communicate with users 1 or 2. Scenarios 4, 5 and 6 were also very similar to one another; the key difference was the type of verbal communication or the lack thereof. As such, their results are presented and discussed together.

Scenario 4 Results

The results for scenario 4 are shown in Figures 4.16 and 4.17 and Table 4.6. There were 3 respondents that submitted answers of "Other" for the second question. Their answers were:

- "Since I was an outside observer to this video, I would expect that if anyone pressed 'undo', it would undo the last action performed by anyone in the part. But, if I were one of the users, I would expect each user to only be able to 'undo' the last action he or she individually did (and not be able to "undo" the actions of other users)."
- "That was the last thing User 2 did."
- "That was the last thing they did."

Scenario 5 Results

The results for scenario 5 are shown in Figures 4.18 and 4.19 and Table 4.7. There were 3 respondents that submitted answers of "Other" for the second question. Their answers were:

- "As an outside observer, I would expect that if anyone presses 'undo', it would undo the last action performed by anyone in the part. But, if I were a user, I would expect that each user would only be able to undo their own features (and not be able to undo the features created by other users)."

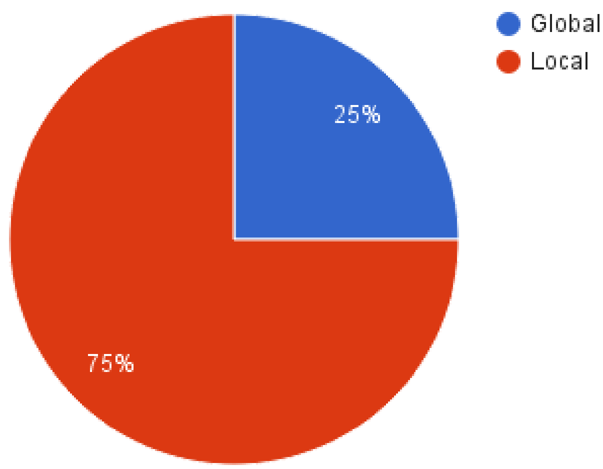

Figure 4.16: Scenario 4 Undo Method Preference

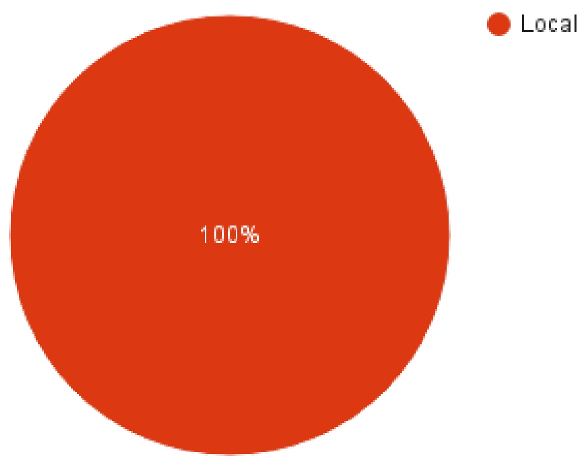

Figure 4.17: Scenario 4 Undo Method Preference - Professionals

- “That was the last action that user performed.”
- “That was the last thing they did.”

Scenario 6 Results

The results for scenario 6 are shown in Figures 4.20 and 4.21 and Table 4.8. There were 6 respondents that submitted answers of “Other” for the second question. Their answers were:

Table 4.6: Scenario 4 Undo Factors

Factor	% of users	% of pro users
All the users were working on unrelated, independent features	65%	50%
The users were NOT discussing the work they were performing	45%	25%
The users were NOT discussing design decisions	40%	25%
The users were all working in the same part	30%	25%
The action you would want to be undone was the last action performed by anyone in the part	25%	0%
You felt the users were NOT working in close proximity to one another	20%	0%
You felt the users did NOT have a shared design intent with one another	20%	25%
Other	15%	50%
User 2 was able to see user 1's actions	10%	25%
User 2 was able to see user 3's actions	10%	25%
There was verbal communication between all of the users	5%	25%
You felt the users were working in close proximity to one another	5%	25%
You felt the users had a shared design intent with one another	5%	0%

Table 4.7: Scenario 5 Undo Factors

Factor	% of users	% of pro users
All the users were working on unrelated, independent features	65%	50%
There was NO verbal communication between any of the users	40%	25%
The users were all working in the same part	35%	25%
The action you would want to be undone was the last action performed by anyone in the part	25%	0%
You felt the users were NOT working in close proximity to one another	25%	0%
You felt the users did NOT have a shared design intent with one another	15%	0%
Other	15%	50%
You felt the users were working in close proximity to one another	10%	25%
User 2 was able to see user 1's actions	5%	25%
User 2 was able to see user 3's actions	5%	25%
You felt the users had a shared design intent with one another	5%	0%

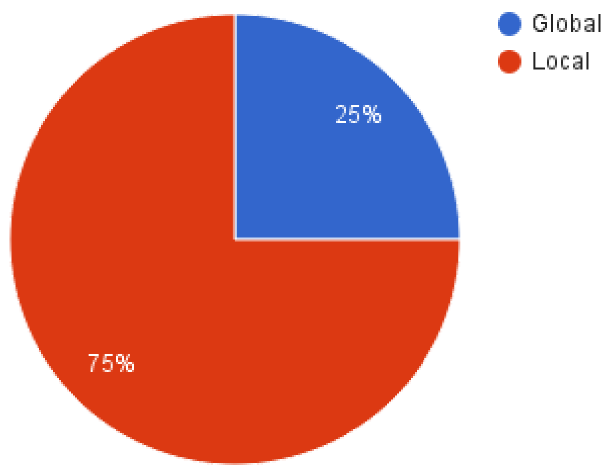

Figure 4.18: Scenario 5 Undo Method Preference

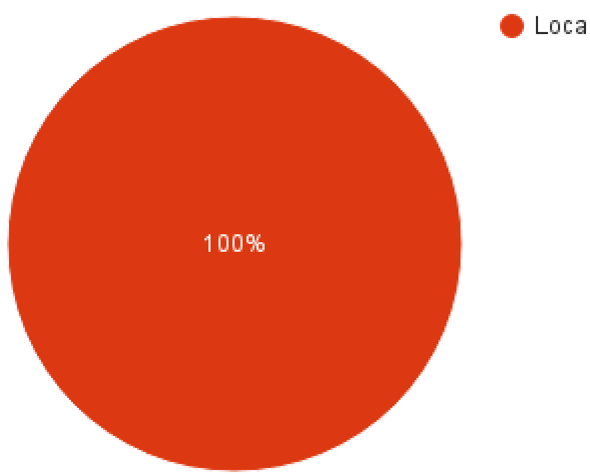

Figure 4.19: Scenario 5 Undo Method Preference - Professionals

- "I was an outside observer to this video. Because of this, I expect that if any user presses 'undo', it will undo the last action performed by anyone in the part. But, if I were a user, I would expect that each user could only undo their own actions, not the actions of other users."
- "User 2 seemed to get collaboration from U3 (I'm not sure about U1) but didn't really seem to collaborate back on other features performed afterwards."
- "User 2 didn't create features dependent on other features."

- “Users 2 and 3 were discussing decisions and working more closely together.”

- “That was the last thing they did.”

- “There is a dependency between the extrude and the chamfer, but less of a dependency between the sketch and the chamfer.”

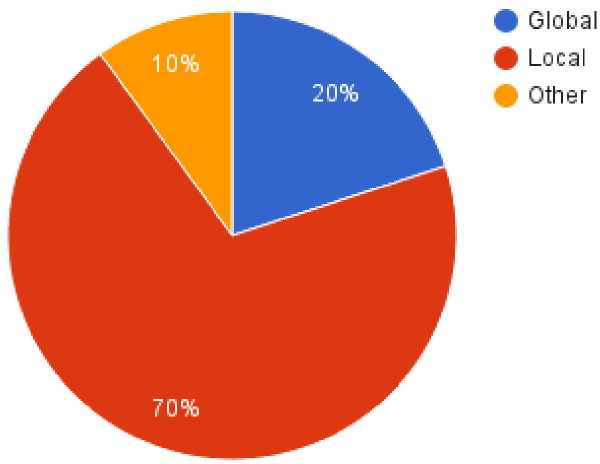

Figure 4.20: Scenario 6 Undo Method Preference

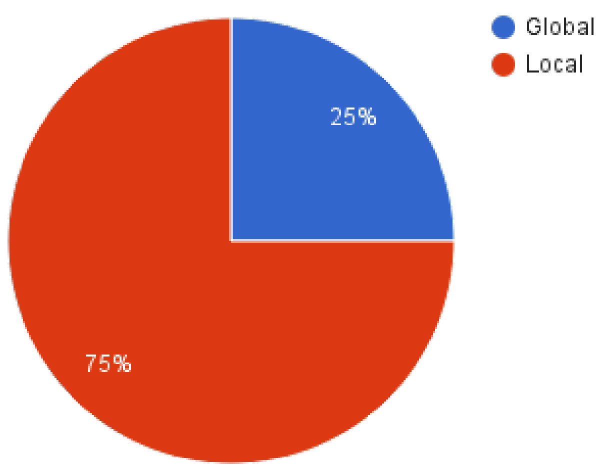

Figure 4.21: Scenario 6 Undo Method Preference - Professionals

Table 4.8: Scenario 6 Undo Factors

Factor	% of users	% of pro users
All the users were working on unrelated, independent features	55%	50%
Other	30%	50%
The users were all working in the same part	30%	25%
You felt the users were NOT working in close proximity to one another	25%	0%
The action you would want to be undone was the last action performed by anyone in the part	25%	0%
The users were discussing the work they were performing	15%	25%
The users were discussing design decisions	15%	25%
There was verbal communication between all of the users	10%	25%
User 2 was able to see user 1's actions	10%	25%
You felt the users were working in close proximity to one another	10%	25%
User 2 was able to see user 3's actions	10%	25%
You felt the users had a shared design intent with one another	10%	25%
You felt the users did NOT have a shared design intent with one another	5%	0%

Discussion of Scenarios 4, 5, and 6

As mentioned previously, the key difference between these 3 scenarios was the type of verbal communication or lack thereof. In scenario 4, the users were all talking about sports rather than the work they are doing. Scenarios 4 and 5 were identical with the only difference being that scenario 5 has no audio; it was the same video as scenario 4 with the audio track removed. Scenario 6 was a very similar scenario with the difference being that the users were talking about the work they were doing. In all 3 scenarios, the respondent was asked what they would expect to happen if user 2 pressed undo.

These 3 scenarios looked at if verbal communication alone was enough to influence undo expectations. This emphasis is important due to the significance placed on verbal communication by users during the design exercises. These scenarios also provided an additional opportunity to look at users' expectations regarding global undo in a few slightly different scenarios.

Together, these 3 scenarios produced almost the exact same results. In all 3 scenarios, respondents strongly favored local undo (75% for scenario 4, 75% for scenario 5, and 70% for scenario 6). In addition, the majority cited the fact that the users were working on independent features as a factor in their decision regarding which action to undo (65% for scenario 4, 65% for scenario 5, and 55% for scenario 6). Other than that, no other factor seemed to play a consistent role for users. This similarity, however, is a very useful result: it provides strong evidence supporting the fact that while verbal communication is an important criteria for a shared undo stack to be used, it's presence alone is not enough to affect whether a user prefers a shared undo stack or not.

4.4.5 Scenarios 7 and 8

As with scenarios 4, 5 and 6, scenarios 7 and 8 were similar to one another. They sought to study what effect dependencies has on users' undo expectations. Their results are presented and discussed below.

Scenario 7 Results

The results for scenario 7 are shown in Figures 4.22 and 4.23 and Table 4.9. There were 3 respondents who submitted answers of "Something else" for the first question. Their responses were:

- "Ask the user whether they want to undo both their and User 2's actions, or if they want to only undo User 2's action." This answer is similar to the answer to confirm their undo action, but it instead allows the user to choose which specific action to be undone.
- "Undo the creation of the mirror after prompting the user." This answer was coded as an answer to undo the creation of the mirror.
- "Similar to "Ask whether to undo or not due to the dependency of someone else's feature and allow the user to confirm or cancel their undo action. If they confirm, undo both the creation of the cylinder subtractions and the mirroring of the cylinder subtractions." but give the choice to either undo the subtraction & mirror or just the mirror." This answer is similar to the answer to confirm their undo action, but it instead allows the user to choose which specific action to be undone.

There were 4 respondents that submitted answers of "Other" for the second question. Their answers were:

- “Since I was an outside observer, I would expect that if any user presses ‘undo’, it would undo the last action performed by anyone in the part. But, if I were one of the users, I would expect that each user could only undo their own actions, and not be able to undo the actions of other users.”
- “It didn’t feel like there was any true collaboration (Back and forth, advice).”
- “The last thing they did would invalidate something someone else did, telling them that they can’t undo their last action places the burden of fixing things on them.”
- “It was unclear if user 1 was working with user 2 on the mirror. Because it is unclear (especially unclear to the computer) and user 2’s action is dependent on user 1’s action, give user 1 full disclosure and ask what they mean by the undo”

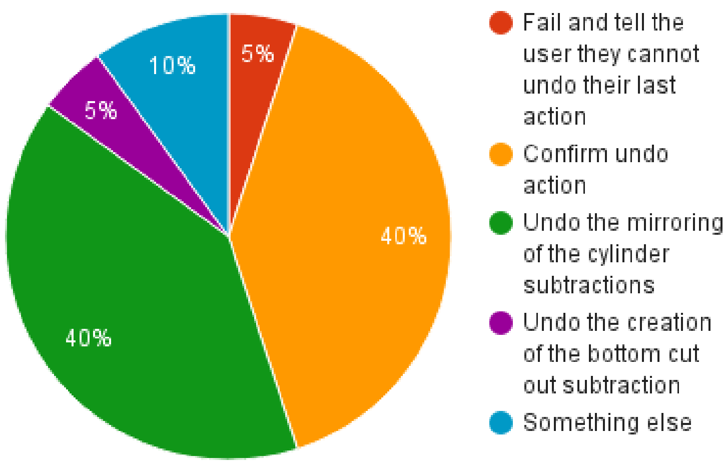

Figure 4.22: Scenario 7 Undo Method Preference

Scenario 8 Results

The results for scenario 8 are shown in Figures 4.24 and 4.25 and Table 4.10. There were 4 respondents who submitted answers of “Something else” for the first question. Their responses were:

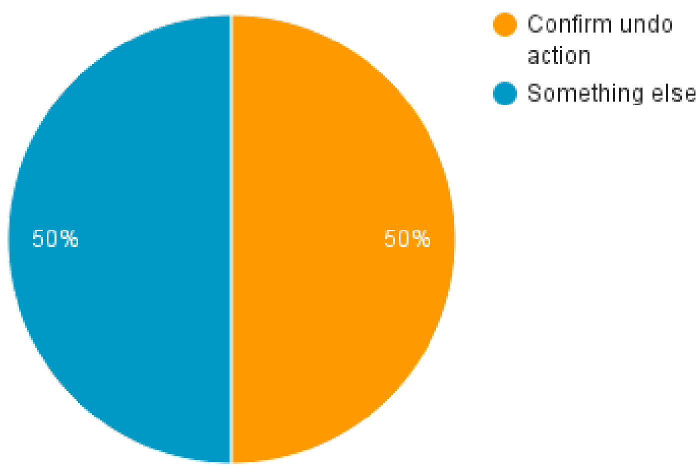

Figure 4.23: Scenario 7 Undo Method Preference - Professionals

Table 4.9: Scenario 7 Undo Factors

Factor	% of users	% of pro users
The users were discussing the work they were performing	50%	25%
User 2's last action was dependent on user 1's last action	45%	75%
The users were all working in the same part	45%	25%
You felt the users were working in close proximity to one another	40%	25%
You felt the users had a shared design intent with one another	40%	25%
There was verbal communication between all of the users	35%	25%
Users should not be able to undo something with a dependency if another user created the dependency	30%	0%
User 1 was able to see user 2's actions	25%	25%
The users were discussing design decisions	25%	25%
The action you would want to be undone was the last action performed by anyone in the part	25%	0%
Other	20%	50%
User 1 was able to see user 3's actions	10%	25%
You felt the users were NOT working in close proximity to one another	0%	0%
You felt the users did NOT have a shared design intent with one another	0%	0%

- "Ask the user of they want to undo both their and User 2's actions, or if they just want to undo User 2's action." This answer is similar to the answer to confirm their undo action, but it instead allows the user to choose which specific action to be undone.

- “After prompting, undo the creation of the mirror due to it being dependent on the last feature created by the user.” This answer was coded as an answer to undo the creation of the mirror.
- “third option and then if they confirm it notifies user two that their action was undone.”
- “Similar to “Ask whether to undo or not due to the dependency of someone else’s feature and allow the user to confirm or cancel their undo action. If they confirm, undo both the creation of the cylinder subtractions and the mirroring of the cylinder subtractions.” but give the choice to either undo the subtraction & mirror or just the mirror.” This answer is similar to the answer to confirm their undo action, but it instead allows the user to choose which specific action to be undone.

There were 3 respondents that submitted an answer of “Other” for the second question. Their answers were:

- “Since I am an outside observer to this video, I felt that when anyone presses ‘undo’, it should undo the last thing done in the part (by anyone). But, if I were a user, I would want each person to be able to undo only the last thing he or she did individually (and not be able to undo the actions of other users).”
- “Undoing the last thing they did would invalidate something someone else did.”
- “While the users were obviously not collaborating, undoing user 1’s action would affect user 2’s action. Furthermore, user 1 saw that his subtraction was mirrored. A dialog box with clarification on what should be undone would enable the user to select his intention.”

Discussion of Scenarios 7 and 8

In scenarios 7 and 8, the users were all talking to one another and user 2 performed an action that was dependent on user 1’s action by mirroring the cylinder subtractions of the engine block. The respondent was then asked what they would want to happen if user 1 pressed undo. The key difference between the two scenarios is that in scenario 7, the users were discussing the work they are doing while in scenario 8 they were talking about camping. These scenarios also differ from the previous 6 scenarios because two of the answers included other undo models: alerting the

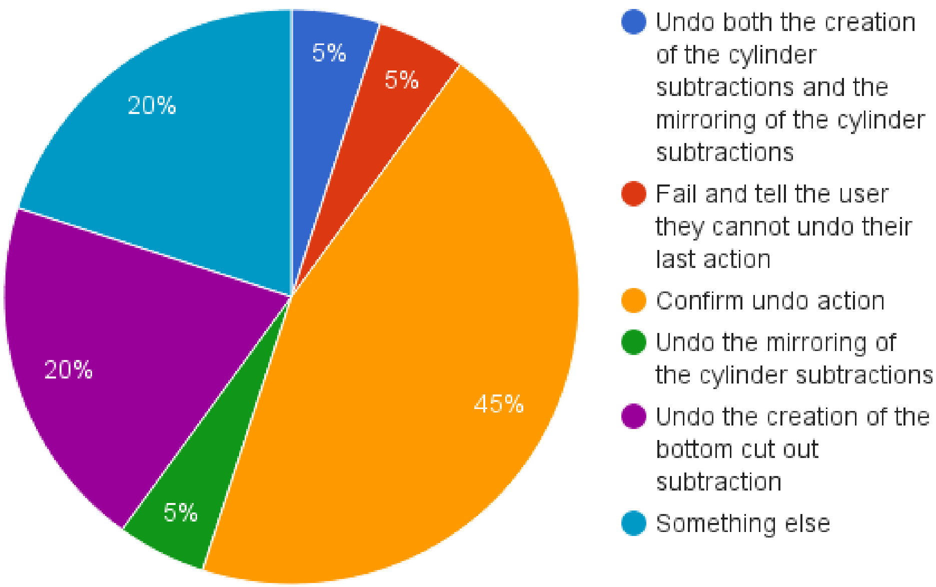

Figure 4.24: Scenario 8 Undo Method Preference

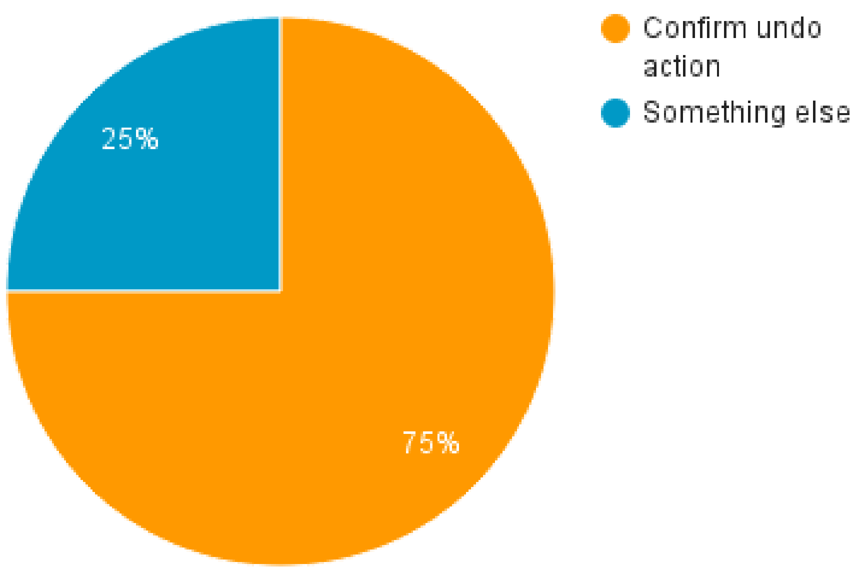

Figure 4.25: Scenario 8 Undo Method Preference - Professionals

user that they are unable to perform this undo action due to the dependency and warning the user that they are going to undo an action with dependencies, but allowing them to confirm and undo both their action and the dependent action.

Table 4.10: Scenario 8 Undo Factors

Factor	% of users	% of pro users
User 2's last action was dependent on user 1's last action	45%	75%
The users were all working in the same part	45%	25%
You felt the users were working in close proximity to one another	30%	25%
The action you would want to be undone was the last action performed by anyone in the part	30%	0%
Users should not be able to undo something with a dependency if another user created the dependency	30%	25%
You felt the users had a shared design intent with one another	25%	0%
User 1 was able to see user 2's actions	20%	25%
There was verbal communication between all of the users	15%	25%
Other	15%	50%
You felt the users did NOT have a shared design intent with one another	15%	25%
You felt the users were NOT working in close proximity to one another	5%	0%
User 1 was able to see user 3's actions	5%	25%
The users were discussing the work they were performing	0%	0%
The users were discussing design decisions	0%	0%

In both of these scenarios, almost half of respondents (40% for scenario 7 and 45% for scenario 8) expected the undo action to be confirmed before being executed. This confirmation workflow ought to be further studied as a possible option for handling the undoing of dependencies when users are not sharing an undo stack.

Another interesting observation in scenario 7 is that 40% of respondents wanted to undo user 2's action of mirroring user 1's action, which represented a shared undo stack preference. Though still a minority of users, this scenario warrants further study; namely, exploring how dependencies play a role in a user's expectations regarding a shared undo stack.

It also illustrates the importance of users verbally communicating about the work being done because the content of the communication was the only major difference between scenarios 7 and 8. In scenario 8, 5% of respondents said they would want to undo user 2's mirroring action. Thus, there is strong evidence that the type of verbal communication coupled with the action on the dependency had a noticeable impact on users' expectations.

Dependencies

One aspect of multi-user CAD that sets it apart from other multi-user tools is the dependencies that exist between features; these scenarios attempted to study this difference. Other systems such as large interactive whiteboards or collaborative document editing such as Google Docs have little or no dependencies between operations; if they are present they are limited to simple things such as formatting or image placement. In contrast, CAD often has complex mathematical relationships that govern the dependencies between features. Given this complexity, undo implementations must take this into account, as evidenced by the implementation of local undo by French et al. [4]. In addition, many participants of this study mentioned the role that dependencies played in their expectations regarding undo. Thus, future prototypes should continue to take this into account, and the usability of the mechanisms to handle dependencies ought to be tested further.

4.4.6 Discussion of Industry Professionals' Responses

Though the sample size is very small, the results from the professionals in industry are promising. For scenarios 2, 3, 4, 5, and 6, more than 75% of respondents for both the students and the professionals preferred local undo. For scenarios 7 and 8, at least 50% of both groups expected the undo action to be confirmed by the user before proceeding. In scenario 1, at least 50% of both student and professional respondents expected regional undo. However, a major discrepancy is that 50% of professional users also expected local undo. It is worth noting though that one of the professional users expressed their opinion that undo should always be local, no matter the scenario; they selected other for every response to the question about undo factors and stated that they felt that the undone action should be the user's last action. Overall, the results seem promising as the students' responses seem to roughly correlate with the professionals responses.

4.5 General Discussion of Results

A general discussion of the results is provided below. The various undo methods are discussed in the context of the results. In addition, some implementations regarding undo are proposed based on the findings of this study.

4.5.1 Global Undo

As a result of this study, global undo, in which the undo stack is shared between all users in an environment regardless of any other factor, is not an acceptable undo method. This finding is consistent with the findings of the whiteboard study, the initial expectations survey, conversations with users during the design exercises, and the follow up survey [1]. As shown previously in the initial expectations survey, only 20% of users expected global undo when presented with a hypothetical scenario. In addition, in the follow up survey, global undo never represented the expectation of more than 25% of users. In addition to the data, during discussions with participants, some were presented with a hypothetical scenario. In this scenario, global undo would lead to an action being undone that the user had no knowledge of. Upon being presented with this scenario, most participants acknowledged that this would be undesirable behavior.

4.5.2 Local Undo Stack vs. Shared Undo Stack

As discussed previously, users do not expect to have a shared undo stack in a majority of scenarios. However, there are a few scenarios in which users do expect a shared undo stack. Due to these changing expectations, an implementation of undo in multi-user CAD ought to be dynamic by providing users two different undo modes and the ability to switch between them: local undo stack mode and shared undo stack mode.

A simple implementation could be completely manual: allow a user to press a button to enter shared undo stack mode and pick a user to share their undo stack with. Upon acceptance by the other user, a new shared undo stack is created and it initially contains no operations. However, the user's previous actions that were done outside of the shared undo stack will remain for them to undo if their current shared undo stack is empty. In addition, upon leaving the shared undo stack state, users revert to a local undo stack and any new actions will only be able to be undone by them. While in the shared undo stack state, all actions that either user performs are added to their shared undo stack in the order in which they are completed. If either user issues an undo command, the last action on the shared undo stack is undone, regardless of the user who performed it. This implementation would allow users to easily leave and enter a shared undo stack state. For a simple implementation, the shared undo stack would be reset when the users exit the shared undo stack state and their actions would return to their place in their respective local undo stacks. If the users enter the shared undo state with one another again, a new shared undo stack is created and any new actions either user takes will be added to this shared undo stack.

4.5.3 Automatic Collaboration Detection

While the manual implementation would provide a usable experience for users, it would make multi-user CAD even more powerful if the software was able to automatically determine if two users are collaborating closely enough to enter a shared undo stack state. This would allow users to work without having to remember to enter a shared undo stack state; the software would simply behave in accordance with their expectations given the situation they were in. As previously mentioned, multi-user functionality such as undo should "blend transparently within existing CAx tools;" automatic collaboration detection would help achieve that transparency [11].

In order to even contemplate an automatic solution, a few things about collaboration must be discussed. It is important to realize that collaboration is a spectrum. During the post exercise assessments, 100% of participants felt they were collaborating with the other users at at least some level. However, as evidenced by their undo expectations, the simple fact that they were collaborating was not enough for them to want to share their undo stack with another user. Contrast this with the results of scenario 1 of the follow up survey; here, many users felt that this was a scenario in which a shared undo stack would be the expected behavior. Therefore, the challenge is how the software can determine if two users are in a scenario in which they would want to share their undo stack.

This determination is what will be called the "shared undo collaboration threshold." This threshold represents the level at which two users feel they are collaborating closely enough to shared an undo stack. For the interactive whiteboard study, the best way to determine this threshold was to use a Microsoft Kinect to determine the location of all of the users around the whiteboard. Based on their location, the software calculated their field of view and then treated any overlap between users as an area in which they were above the collaboration threshold and should thus share an undo stack; this would be analogous to the viewing frustum in CAD [1]. In contrast, this study found that users' expectations in this regard were much more nuanced than in the whiteboard study: while the ability to see another user's actions played a role in determining how close users were to the collaboration threshold, it was not the only factor.

Collaboration Threshold Equation

Due to the complex nature of the shared undo collaboration threshold in multi-user CAD, a collaboration threshold equation is proposed that dictates when two users have reached the collaboration threshold and should now share their undo stack with one another. This is presented below in Equations (4.1) and (4.2).

$$\Psi_{ij} = K_c x_c + K_d x_d + K_p x_p + K_v x_v + K_s x_s \tag{4.1}$$

where

$$K_c + K_d + K_p + K_v + K_s = 1 \tag{4.2}$$

In Equation (4.1), the shared undo collaboration threshold value, Ψ_{min} is 1. The values of each collaboration parameter x are provided below:

- x_c: verbal communication about the work the users are doing
- x_d: discussion about the users' design decisions and intent
- x_p: users' proximity to one another
- x_v: whether a user's view frustum includes the actions of the other user
- x_s: whether the users are working on the same feature at the same time

The K coefficients represent the weights given to each individual component of the equation and Ψ_{ij} represents the calculated collaboration threshold between user i and user j.

Initially, each of the collaboration parameters is a boolean represented as a 1 or a 0, depending on if the condition is true or not. The weights are initially equal to one another such that

$$K_c = K_d = K_p = K_v = K_s = .2 \tag{4.3}$$

but may be adjusted as needed. With equal weights and boolean values for the collaboration parameters, the initial equation serves as a list of criteria that must all be fulfilled in order for two users to enter a shared undo stack state. However, with further research, instead of being booleans the collaboration parameters could be calculated by taking measurements and normalizing the values measured. Examples of how to measure the collaboration parameters are provided below:

- x_c: measure the frequency of verbal communication by monitoring how often users i and j speak
- x_c and x_d: use language processing to analyze the content of the users' communication and assign a score based on how much the users are talking about the work they are doing and their design decisions and intent; also measure how often the users address one another as opposed to other users
- x_p: a user's position can be measured based on their zoom level and the orientation of the part
- x_v: measure what percentage of user j's actions over the past n minutes have fallen within user i's view frustum
- x_s: track whether user i has edited user j's feature within the last m seconds or measure how long it has been since user i has edited user j's feature

These values would constantly be evaluated in real time by the software and if $\Psi_{ij} \geq \Psi_{min}$, then users i and j would enter a shared undo state. Note that initially, the collaboration threshold is shared between users. Additional work could be done to study the feasibility of individual users having their own threshold equation and then once both users' individual Ψ values were above Ψ_{min}, the threshold would be met.

One of the advantages of using an equation in this way is its flexibility. The weights can be adjusted as more research is done and even customized for different users, parts, assemblies, teams, departments, companies, and perhaps even industries. In addition, machine learning can be incorporated to learn more about users and their undo preferences based on actions such as if they manually enter or exit a shared undo stack state. Also, additional collaboration parameters could be added if needed or as further research or machine learning discover additional factors that influence users' expectations.

This equation was derived based on feedback from users during the design exercises and from the results of scenario 1 in the follow up survey. Based on the users who expected regional undo in scenario 1, the factors that influenced their decisions were considered. If a factor from Table 4.2 had 60% or more of users who cited it as influencing their decision, it was included as a term in the equation. Note that some factors were combined: "verbal communication" and "discussing the work they were performing" as well as "having a shared design intent" and "discussing design decisions".

4.5.4 UI Considerations

While automatically changing between undo stack states may make undo easier to use, many users were concerned about unexpectedly undoing other user's actions. This concern included them not knowing that pressing undo would undo someone else's action instead of their own or that another user would be unaware that their actions could be unexpectedly undone by someone else within the same model. A proposed solution to this would be to provide visual feedback on the screens of both users to indicate that they are currently sharing an undo stack. This could be changing the color of the toolbar or the application window or some other easily noticeable cue for the user. In addition, it would be useful to provide an option to display that undo stack and clearly show what the next operation to be undone would be and which user had performed it. Both of these features would help make it more clear to users what would happen if they were to issue an undo command.

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This study found that global undo aligned with the expectations of 25% or less of users. In addition, in discussions with users, they felt in leads to confusion and is ineffective. As such, it is not recommended to implement global undo in multi-user CAD.

This study also found that users expected a local undo stack in a majority of scenarios and in scenarios in which they felt they were not closely collaborating with other users. Therefore, it is recommended that a local undo stack be used most of the time and in a majority of scenarios. This provides validation for previous implementations of local undo and a local undo implementation such as French's et al. ought to be used [4].

Another finding was that users expected a shared undo stack in a few scenarios where specific criteria were fulfilled. It is important to note that the visibility of other users' actions is not the only criteria that needed to be fulfilled; this stands in contrast to the findings of the interactive whiteboard study, in which users expected a shared undo stack in 86% of scenarios and field of view was the primary and most effective criteria for determining whether users should share an undo stack [1]. Based on this finding, two recommendations are made. First, an implementation that provides a shared undo stack when users are collaborating ought to be developed. Second, users should be allowed to switch between a local undo stack and a shared undo stack. When entering a shared undo stack with another user, that user must confirm that they wish to enter a shared undo stack stack. In addition, a UI indication ought to be provided such as a color box around the application window or changing the color of the tool bar so that both users know they are currently sharing an undo stack.

UX/UI design considerations seek to provide as intuitive of an experience as possible to the greatest number of users. However, with any piece of software, not all users will necessarily be satisfied with the UX/UI decisions made. With this fact in mind, these recommendations are made due to the feedback of a majority of users and seek to align with the expectations of as many users as possible. Also, it worth noting that the contributions proposed by this work focus on the shared undo stack state. When users are not collaborating at a level that warrants a shared undo stack, local undo should be used. As evidenced by the findings of this study, this will be in a majority of scenarios.

5.1.1 Redo

While not explicitly studied, several of these conclusions could also apply to redo. If redo is assumed to always redo the last undone action, as actions are undone in a shared undo stack state, those actions could be moved to a shared redo stack. This redo stack would behave in a similar way as the undo stack in that when a user performs a redo action, the last action on the redo stack is redone and moved back to the undo stack. In addition, a shared revert functionality could be explored where a single action would redo all of the actions currently on the shared redo stack.

5.2 Future Work

One of the purposes of this research is to be a foundation upon which additional research into undo in multi-user CAD can be based. As a result, there are many possibilities for future work which are discussed here.

In order to allow multi-user CAD to better "blend transparently with existing CAx tools" [11], one of the most important pieces of future work is to enable the software to automatically detect when users ought to switch between a local undo stack mode and a shared undo stack mode. This can be accomplished by implementing the collaboration threshold equation:

$$\Psi_{ij} = K_c x_c + K_d x_d + K_p x_p + K_v x_v + K_s x_s \tag{5.1}$$

where each collaboration parameter x is explained below and the K coefficients represent the weights of their corresponding collaboration parameter.

- x_c: verbal communication about the work the users are doing
- x_d: discussion about the users' design decisions and intent

- x_p: users' proximity to one another
- x_v: whether a user's view frustum includes the actions of the other user
- x_s: whether the users are working on the same feature at the same time

Another important piece of future work is to develop various prototypes of undo functionality, including prototypes based on the previous recommendations and the collaboration threshold equation, and then test the effectiveness of those prototypes. Though not a general recommendation of this study, a prototype providing separate local and shared undo commands would warrant further study due to multiple users having suggested it as a possible undo implementation. Additional possible prototypes include persisting undo stacks between sessions and providing multiple implementations of undo that users can switch between using software settings.

Redo warrants further investigation due to the nuances mentioned by Mancini et al. [5]. This could be accomplished by performing similar surveys and studies but this time asking about scenarios involving redo. In addition, the proposed undo prototypes could include various implementations of redo.

Although it was not considered in this research, users' expectations regarding undo in a multi-user sketching environment ought to be explored further. Due the fact that sketching is a 2-dimensional environment, users' expectations regarding undo may align more closely with those of the interactive whiteboard users. However, it is important to note that the sketching environment has dependencies while the interactive whiteboards do not; any comparison between the two ought to take this into account. Thus, both general research into the feasibility and usefulness of multi-user sketching and a study of undo within that environment would both be worth performing. However, worth noting is that many design exercise participants mentioned their hesitance or objection to allowing collaboration within the sketching environment.

Based on the results of scenarios 7 and 8, further exploration of how dependencies affect users' undo expectations ought to be performed. Dependencies could also be explored as a potential collaboration parameter in the collaboration threshold equation.

Regarding the demographics of the participants, additional research could seek to use a more diverse group that closely aligns with the demographics of professional CAD users. Also, it would be interesting to control for and further study the effect that a users' previous experience with multiuser 3D gaming has on their perceptions regarding undo. Finally, conducting similar studies using professional engineers instead of less experienced student users would also yield extremely useful data regarding multi-user undo.

A few additional pieces of future work include the following: Perform a similar study with assemblies instead of parts to make an even stronger distinction between global and regional undo. Explore the relationship between multi-user undo, data consistency, and conflict resolution as studied by Moncur et al. [12]. Study the effect of users entering and exiting a model or assembly. Perform additional tests with a much higher number of users. Explore how physical proximity and time spent initially planning between users affect undo expectations.

In summary, the following pieces of future work ought to be performed:

- develop and test prototypes of undo implementations
- perform a similar study focused on redo
- explore how dependencies affect user's expectations
- use a set of participants that align demographically with professional CAD users
- perform a study with assemblies
- explore the relationship between multi-user undo, data consistency, and conflict resolution
- study the effect of users entering and exiting a model or assembly
- test with more users
- explore the effects of physical proximity and initial planning
- explore undo in the sketching environment

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