



## Analysis and Evaluation of Partitioning Techniques for Multi-User CAD

Jemi Ong<sup>1</sup>, Dan Richards<sup>1</sup>, John Salmon<sup>1</sup> 

<sup>1</sup>Brigham Young University,

Corresponding author: John Salmon, [johnsalmon@byu.edu](mailto:johnsalmon@byu.edu)

**Abstract.** Recent advances into multi-user computer-aided design environments have enabled designers and engineers to work simultaneously on the same model in different locations. This technology enables different individuals and companies across the globe to share 3D model data in more direct ways. However, intellectual property becomes a larger issue when sharing potentially sensitive data with others in real-time. Partitioning techniques are one strategy to mitigate this risk within multi-user CAD environments. This study explores and evaluates six different partitioning techniques across various metrics identified in the literature and performed a user study to assess the methods' capabilities to hide or suppress data from others. Best practices are suggested and survey data from the participants are analyzed. Overall, the Planar Decomposition technique was found to offer the best trade between protecting data, facilitating multi-user design, and encouraging users to focus only on the relevant information for a design activity.

**Keywords:** Partitioning Methods, Multi-User CAD, Planar Decomposition, Multi-Resolution, Envelope Methods

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### 1 INTRODUCTION

The technology of multi-user CAD, where more than one individual can add to, update, and edit a 3D CAD model in real-time, simultaneously and in different locations, has considerable potential to improve and accelerate engineering design [10, 24, 14]. However, with the advent of any new technology, additional ramifications emerge which were initially not addressed at the beginning. In regards to multi-user CAD, the global economy necessitates that companies work together in ever more interconnected ways. However, these collaborations can often require the sharing of data which come at the risk of losing information which one or more parties may consider advantageous to keeping protected. This research explores the capability of partitioning techniques to enable the collaborative processes possible from multi-user CAD while concurrently keeping models and data protected. The historical context in which this technology arises is first described, followed by the detailed motivations for this research. The methodology to evaluate partitioning techniques is then presented followed by the results and discussion of the experiments findings.

## 1.1 Historical Background

The protection of intellectual property, or intangible property of various forms, has always been important throughout history. For example, the Ancient Greeks and Romans, well known for their passion towards human knowledge, condemned the theft of ideas found in their many literary works [17]. After the Renaissance and following cases such as *Davenant v. Hurdis*, thought to be the first case recorded concerning monopolies, England passed the Statute of Monopolies in 1624 to address patents and the problems surrounding their issuing [16]. Since that time, countries have developed patent and copyright laws to provide security for discoveries and inventions. In addition, companies have built protocols to protect company-specific information through trade secrets and nondisclosure agreements. Even so, the technology that exists today, like multi-user CAD, pushes the boundaries of sharing data and human knowledge, making it easier to obtain and transfer new information both legally and illicitly, thus increasing the need to protect intellectual property (IP).

The need to protect intellectual property has also become more urgent as countries with different laws, values, and expectations towards the protection and value of IP are collaborating more now than ever before. In more recent years, this has resulted in the World Trade Organization and agreements such as the Trade-Related Intellectual Property Rights, to add structure to the ever growing world marketplace [6]. Though controversial, they have helped prevent stifling innovation, promote economic growth, and increase competitive advantage by protecting IP and hindering counterfeiting [23]. These organizations and agreements have bolstered collaborating companies into forging greater trust amongst each other and developing new ways to protect their IP. One of the first industries to create new methods was the semiconductor industry who increased their IP protections by digitally watermarking their integrated circuits [13].

Nevertheless, while companies have developed many new methods to protect IP, information is still stolen regularly. Piracy and counterfeiting have led to the loss of billions of dollars from companies around the world. From 1986 to 1996, it was estimated this loss increased 300 percent (61 to 200 billion dollars per year) [23]. Recently, sources of such leaks in information have come not only from insiders, but from outsiders who drain IP through holes in computer networks [1]. These two common forms of dishonest disclosure are compounded in situations where companies collaborate with each other, universities, or the government. However, despite this increase in IP divulgence, collaboration is becoming more common as new computer technologies makes it easier and more efficient to work together. For example, company-university partnerships, such as capstone projects allow senior engineering students to work together with an outside party. During this time, they seek to create an innovative solution to a given problem, which often leads to the development of new, but less protected IP as the information is exposed to multiple parties [9].

One instance of collaboration often seen in capstone projects and other model based projects lies in using CAD software. In this scenario, protecting IP may be found by partitioning the models. This allows one company to restrict specific information from another company, while still providing the information the other company needs as part of the collaboration.

## 1.2 Motivation

When a multi-user CAD program is used to collaborate over a design problem between multiple companies, the need for IP protection is extremely important and needs to be carefully monitored. A synchronous multi-user CAD system introduces factors that makes protecting IP more difficult relative to a conventional, single-user CAD program. During modeling, geometry must update in real time, but the CAD program should enable the accessible information to vary from one company to another. This requires a program complicated enough to adequately restrict information, but simple enough to not slow down real-time updates.

Researchers have already tested different methods to partition information in single-user CAD environments to give a company better control over their CAD models, and in turn, their IP. Nevertheless, tests have yet to be performed in a multi-user CAD setting, which is becoming a necessity with the rising popularity of cloud-

computing and multi-user CAD environments. Subsequently, this paper will evaluate a number of single-user partitioning strategies implemented in a synchronous multi-user CAD program. Understanding which method can hide sufficient amounts of information, but refrains from negatively affecting the multi-user functionalities of the program will be a major step in understanding how to better protect IP in a multi-user CAD environment.

## 2 LITERATURE REVIEW AND CLASSIFICATION

A literature review was first performed to evaluate the current partitioning methods available for single-use CAD. Current multi-user CAD has very little IP protection mostly due to the relative short history of the technology. Subsequently, this literature review is key in pinpointing the best partitioning methods to test for implementation into a multi-user CAD environment that would provide the best protection of intellectual property for all parties.

During the first stages of the literature review, six key requirements were created to define the most important aspects of a partitioning method. Methods that did not fulfill all six requirements were not evaluated further as potential candidates for testing in multi-user CAD. The requirements are as follows:

- Well developed algorithm
- Method has been implemented in current CAD software
- Degree of obfuscated visual information (degree to which user was prevented from gaining data)
- Variability of the obfuscation (degree to which moderator could choose the information obscured)
- Versatility (a method that could be applied to both a single feature and entire part showed more versatility than one that could only be applied to a single part)
- Effect on data transfer and computational speeds

Many of the single-user partitioning methods we studied were related or derivatives of others. As a result, we generated two categories to better define them. The first category defined methods that removed while the second encompassed methods that altered or obscured. These categorizations are shown with a description of each method in Tab. 1 and Tab. 2. Further sub-categorizations were developed in the taxonomy of partition techniques presented in Fig. 1, with examples of each method shown in Fig. 2.

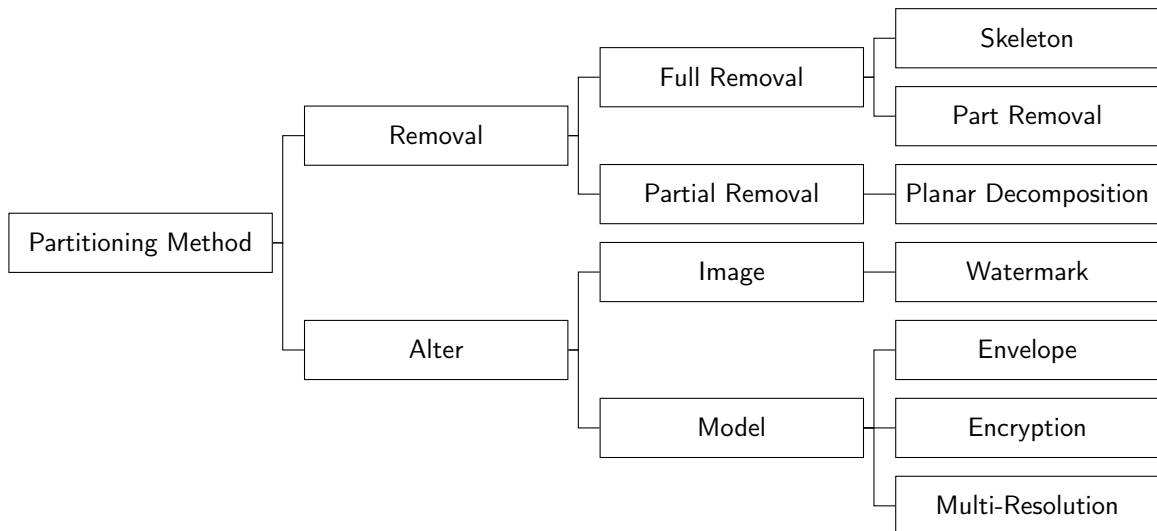
**Table 1:** Removal partitioning methods

Name	Description
Skeleton	Parts are removed from the view of those without the right security level. Only lines and shapes are left behind that provided the needed dimensions for interfacing geometry or constraints for partial-access designers to use.
Part Removal	Removes an entire part from an assembly
Planar Decomposition	Uses planes or surfaces to define regions that are visible to users

In particular, one of the partitioning methods, planar decomposition, was difficult to categorize. It uses planes and surfaces to define visible regions of a model. Within a multi-user setting, this means a user's visuals are based off of planes selected by an administrator to create divisions in the geometry accessible by a user [22]. Since this method mainly uses planes to remove things from view, it could be designated as a Removal Method. However, if a surface is selected by an administrator, it could alter a model by removing features of a specific part, thus giving this method the capability of being an Altering/Obscuring Method as well. In Fig. 2, planar decomposition is illustrated by a plane which divides the turbine into two parts with a single plane. In

**Table 2:** Altering/Obscuring partitioning methods

Name	Description
Envelope	Obscures parts by surrounding them with a three-dimensional solid.
Encryption	Alters parts and features by using an encryption key to change dimensions, which thus affects the appearance of a model.
Multi-Resolution Surfaces	Obscures features by adjusting the coarseness of the mesh that makes up the model. Higher coarseness results in a greater degree of obfuscation.

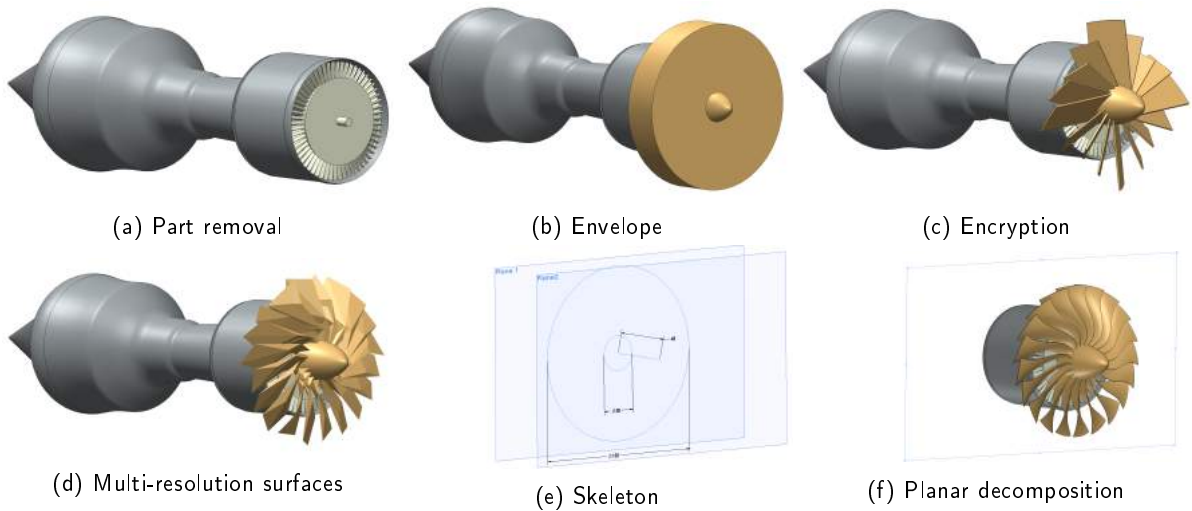
**Figure 1:** Taxonomy of single-user partitioning methods

contrast, it would have been possible to illustrate the altering capabilities of this method by using the surface of the cone to obscure the blades of the turbine from the view or access of another user, thus demonstrating the cross-over between categories.

The other two methods categorized as a Removal Method were skeleton and part removal. As the name "Part Removal" suggests, any number of parts can be removed from view in an assembly, making it impossible to gain any information about these excluded parts [5]. Skeleton is similar to part removal, in that it removes the entire part from an assembly. What sets skeleton apart is that it leaves behind planes and sketches giving general dimensions of the removed part that may be referenced by the user [18]. These methods can be seen in Fig. 2 where part removal hides the fan entirely and the skeleton technique shows only the general spatial dimensions of the fan, often sufficient data for collaboration purposes.

The Altering/Obscuring Methods consisted of envelope, encryption, and multi-resolution surfaces. Envelope is one of the methods already found in CAD software, such as Siemens NX where it is known as "wrap." This method takes a model and encompasses the selected parts in a three-dimensional solid to effectively obscure any recognizable dimension or quality from the model [5].

As far as the study could ascertain, encryption is unlike envelope in that it is a method not yet implemented in commercially available CAD software. This method uses an encryption key on specific parts to alter their dimensions [2, 3]. Thus the part remains in the model for visual representation, but unauthorized users are



**Figure 2:** Examples of the single-user partitioning methods described in Tables 1 and 2

restricted from obtaining information about the true shape, size, or quantity of the features in a part. In the turbine engine example of Fig. 2, the number of blades, curvature of the fan blades, and angle of the blades could be encrypted to prevent access to these parameters.

The third altering method, multi-resolution surfaces, reduces the polygon count in the mesh of a model, effectively reducing the resolution of the surfaces [4, 11, 12, 15, 19, 20]. The more coarse the mesh, the more the part is obscured. Figure 2 shows the fan of the engine with triangular facets simplifying the curvature of the original fan.

Two methods described in the literature did not pertain to either category. The first, watermarking, is a very dated method of intellectual property protection and is more common on printed documents or integrated circuits than on three-dimensional models [21]. The second, differing level of detail, was less a definite partitioning method as it was more focused on administering the degree or level of partitioning based upon the security clearance or role of employees [4, 5, 7, 8, 12].

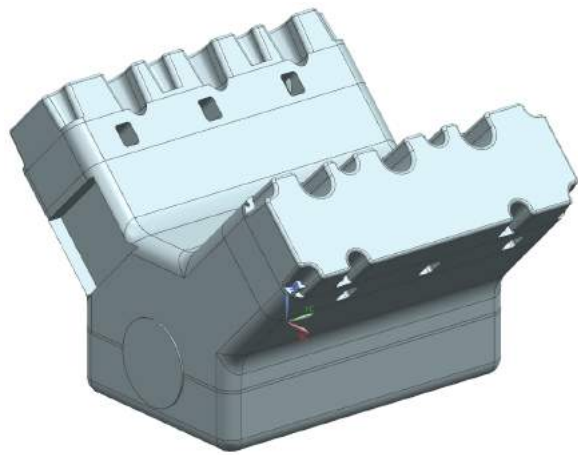
After the preliminary evaluation of the partitioning methods against the key requirements presented above, four partitioning methods stood out as candidates for further exploration within multi-user CAD environments: encryption, envelope, multi-resolution, and planar decomposition. All four indicated high levels of variability in application and were already well documented and tested.

### 3 METHODOLOGY

Considering the top four methods remaining after the down-selection process, an experiment was designed to explore their capabilities and appropriateness for implementation in a multi-user CAD environment. The envelope (EN) method was included in testing because of its current implementation in existing CAD software for single users. Testing EN would allow it to be evaluated and compared to the other partitioning methods, thus identifying if it is sufficient to meet partitioning criteria in multi-user CAD. Planar Decomposition (PD) and multi-resolution surfaces (MR) were included in testing and were expected to perform the best based on the reviewed literature. Early exploratory tests found that functionally, the results of encryption were identical to those represented by the MR method. Subsequently, encryption was dropped from the experimental set as conclusions with MR can generally be applied to encryption as well.

Experiments were run with these three partitioning methods (i.e. MR, PD, and EN) on four different assemblies (Shock Absorber, Boiler Feed Valve, Turbofan, and V6 Engine). The assembly models were selected from various industries in which multi-user CAD could be applied with partitioning methods and differing levels of complexity.

In every assembly, two parts were removed. For the tests, two people in a multi-user environment would each model one of the two parts. The removed parts met two main criteria. First, the part had to be simple enough that testers could complete the task within 10 to 12 minutes. Second, the part had to rely on dimensions from another part of the assembly (e.g., coincident to a face, interfacing shaft-hole relationships, or equal hole sizes). These criteria allowed normalization of the data across the four models.



**Figure 3:** V6 engine before any partitioning modifications were made

Each assembly was then modified to simulate the three partitioning methods (i.e. MR, PD, and EN) in the multi-user setting. The tools used to simulate partitioning in NXConnect were layers, allowing the locking or hiding of specific components for individual users within NXConnect, section views, and a 3D program called Blender for the MR parts.

For example, in one model, a V6 engine (Fig. 3), planes were added and used to create section views which simulated the PD environment as seen in Fig. 4. To simulate MR, STL files were manipulated in Blender to reduce the resolution and give the part an MR appearance (Fig. 5a). The MR files were imported as STL files back into the assembly and put on individual layers. EN partitioning was simulated by using extrudes to block out features and left only the general outline of the part (see Fig. 5b). These extrusions were put on a separate layer and locked so that during tests, users would be unable to click on or obtain information (such as dimensions) about the obscured extrusion. Similar processes were used in each of the other assemblies. Thus, in a multi-user environment, the contracting company would view the unmodified assembly while the contractor(s) would see a partitioned model. Whether or not the user has unmodified or partitioned access to the assembly, real-time updates would still be received. As a result, if a full-access user made modifications that should not be accessible to the contractor, the contractor would see an update in their multi-resolution, envelope, or planar version of the assembly.

### 3.1 Description of Experiments

At the beginning of each test, proctors explained to the users how partitioning worked, that they were going to try out three different methods each with a different model within a multi-user CAD environment, and that they would have 12-15 minutes to model a part within the assembly. The image of the missing part they were to model was provided on a slip of paper. The location and constraining geometry were also shown to each user. The participants were asked to answer the pre-survey questions prior to beginning each model design in order to get the participants to think about the partitioned assembly and the amount of information they could pull from it. Participants would then begin modeling after completing the survey. Two users were present for each test, but their parts did not overlap. As a result, each user provided us one data point for our results. A

visual representation of how the partitioning methods and models were permuted between the different user subjects in the test is presented in Tab. 3.

**Table 3:** This represents the testing plan and assignment matrix. Each symbol ( $\star$ ,  $\diamond$ ,  $\aleph$ , or  $\triangle$ ) represents a different pair of users and how the parts they modeled varied amongst the different partitioning methods. With 17 user-subject pairs, the method-model combinations were mostly evenly distributed among all the groups. The number in parentheses shows the number of times that particular partitioning method-model combination was tested.

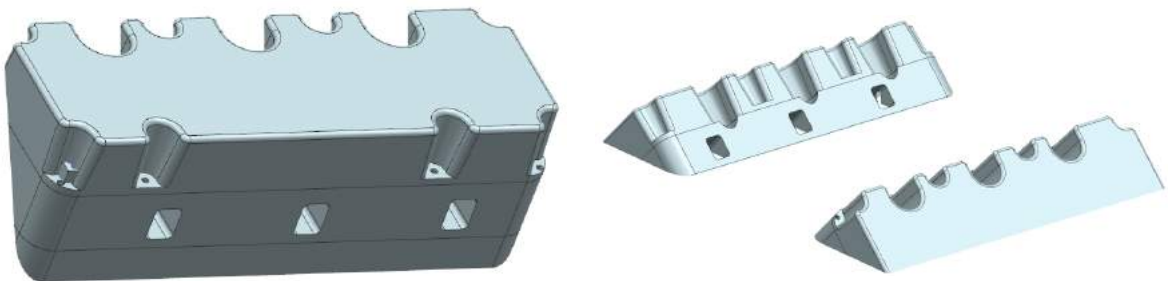
	Multi-Resolution	Planar Decomposition	Envelope
Shock Absorber	$\star$ (5)	$\diamond$ (4)	$\aleph$ (4)
Turbo Fan	$\diamond$ (4)	$\star$ (4)	$\triangle$ (4)
V6 Engine	$\aleph$ (5)	$\triangle$ (4)	$\star$ (4)
Boiler Valve	$\triangle$ (5)	$\aleph$ (4)	$\diamond$ (4)

All modeling was performed in NXConnect, a multi-user CAD environment, with one other participant. To better simulate a multi-user environment, while limiting unnecessary interference between participants, a moderator was present to enter the assembly at the six or seven minute mark and change the dimensions of the users' reference geometry and observe the participants reactions. At the completion of the modeling phase, a post-survey questionnaire was administered to each user to determine how they perceived the capabilities of each method and to provide feedback about their experience with the three partitioning methods.

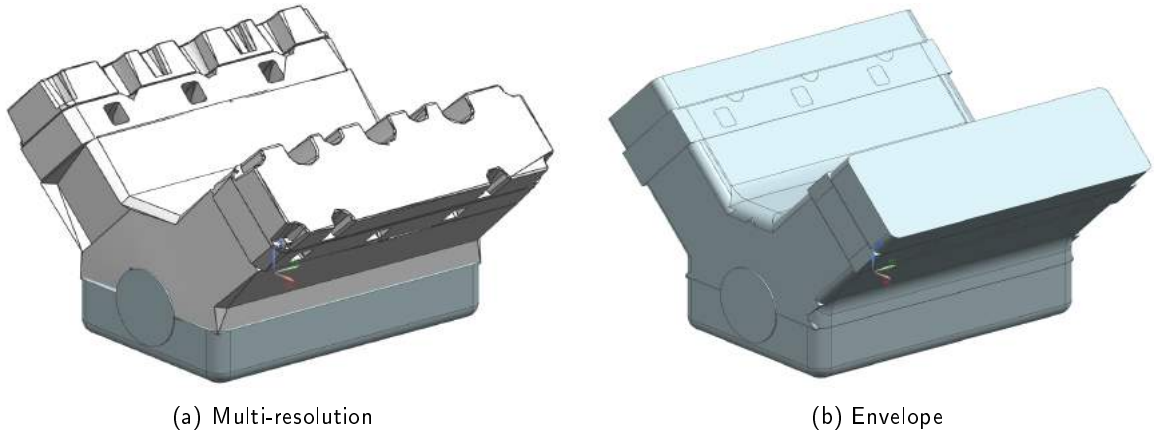
At the completion of the testing, the users were able to provide feedback about their experience with the three partitioning methods. Each combination of assembly and partitioning method was used an approximately equal amount of times although some assembly-partitioning method permutations were used slightly more than others (see Tab. 3).

### 3.2 Limitations of Methodology due to NXConnect

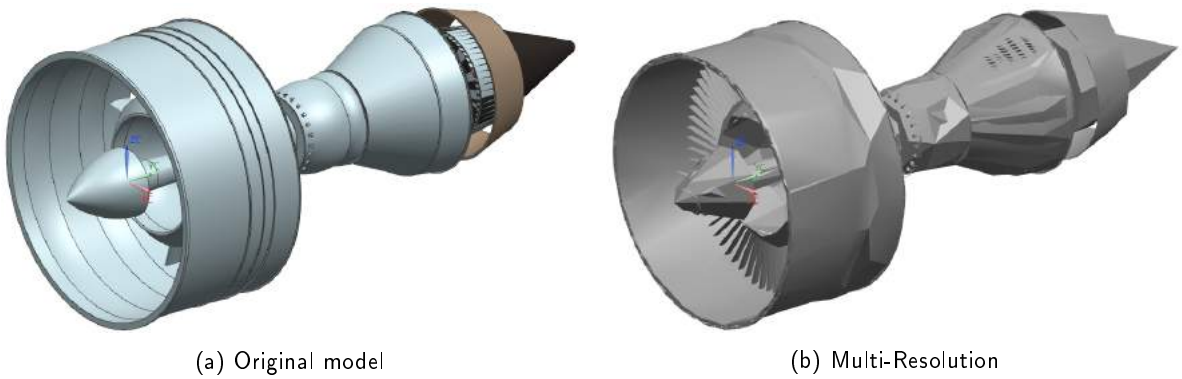
During the experiments, a number of consistency errors occurred within the research multi-user CAD software, NXConnect (NXC). As a result, users had less time available to complete their modeling and changes made to the model would not always update. Another limitation of NXC is that the multi-user environment was not associative. Changing base features in models of the complexity used in the experiments caused NXC to crash. Thus, in order to simulate a change in the reference geometry, an extrude was often used to cut or expand. Subsequently, user's work would not update (from a lack of associative links) which caused frustration that



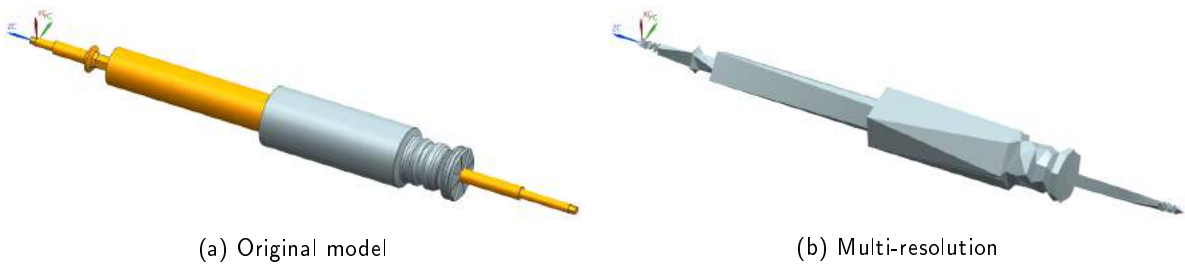
**Figure 4:** Two different V6 engine planar views



**Figure 5:** Example partitioning methods of V6 engine



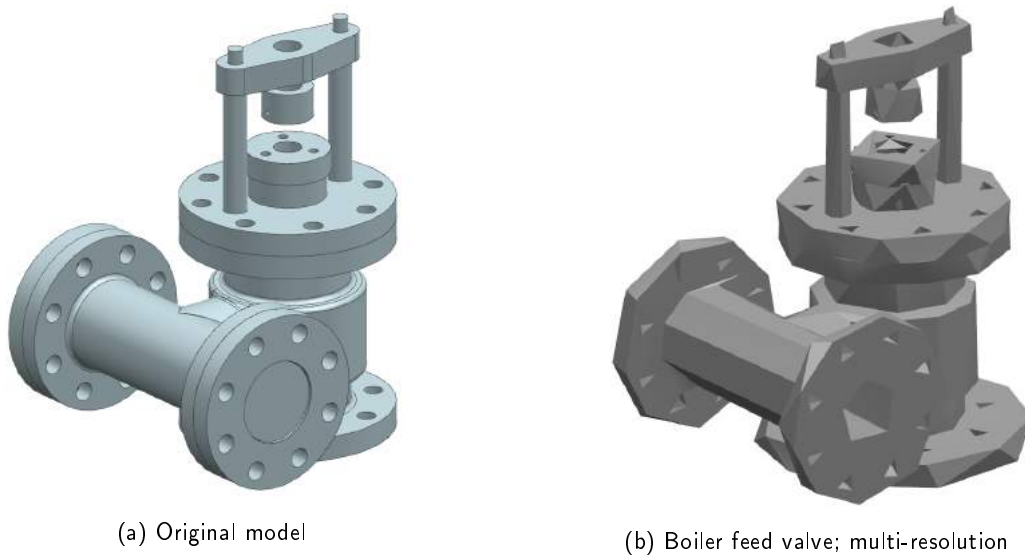
**Figure 6:** Example model of turbofan



**Figure 7:** Example model of shock absorber

users may have associated with the partitioning methods themselves. Additional frustrations resulted from extruded changes that occasionally engulfed a user's original sketch/extrude, rendering them unable to find it. Although these errors did occur during testing, they generally occurred evenly across experiments, and thus the results and conclusions are still valid.





**Figure 8:** Example model of boiler feed valve

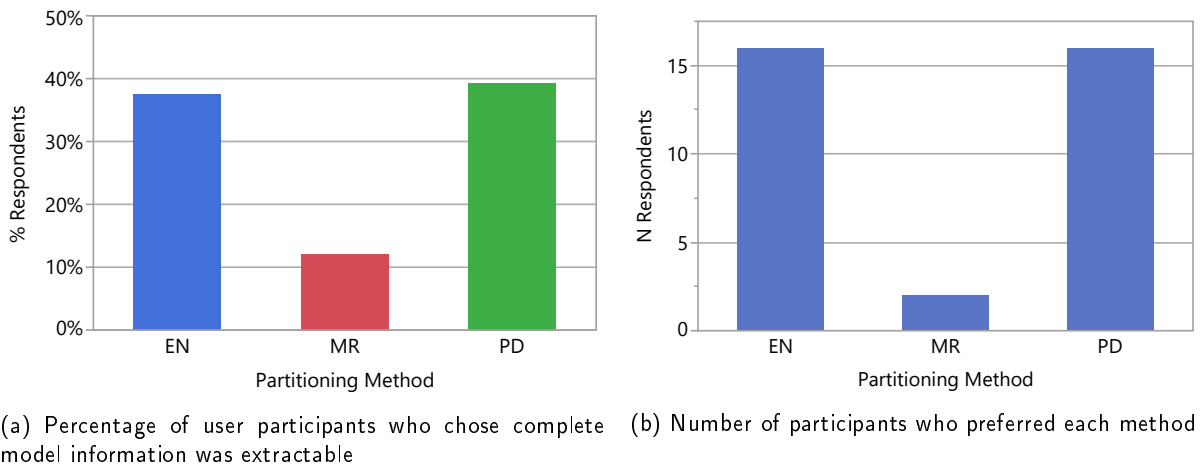
#### 4 RESULTS

In the pre-survey given before each round of modeling, users were asked if they thought they had the required information to model their respective part. When asked this question, 65.7% of users responded “No” prior to modeling with a part partitioned based on MR. This was slightly unexpected because planar decomposition, which only showed a small portion of the part, was the method users most often stated they had sufficient information. The results of this survey question indicate that seeing a whole assembly is of far less value compared to being able to access and use the reference geometry.

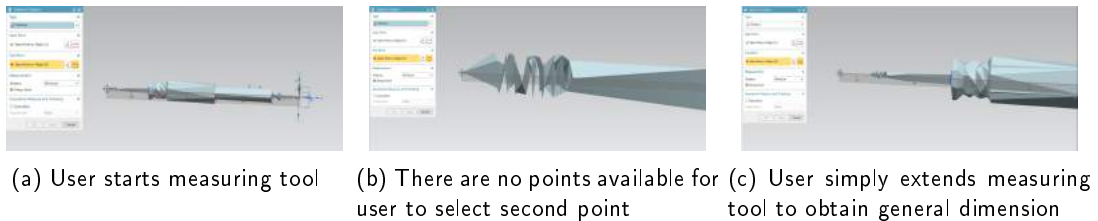
Additionally, we repeated this question in the post-survey where the majority of users once again indicated MR was the most difficult to use (see Fig. 9a). This question was graded on a scale of one to five (with a five indicating all necessary features could be seen). Only 12.1% found this to be true for MR, which is very low compared to the number of people who gave a five for the other two methods—39.3% for PD and 37.5% for EN. Furthermore in Fig. 9b it is clear that users would much rather model with either envelop or planar decomposition. The combination of these two graphs in Fig. 9a and 9b supports the earlier conclusion that users valued being able to see and reference features they needed in order to model effectively.

The conclusions from the surveys were also supported by proctor observations. Depending on the partitioning method used, users attempted various methods of finding or extracting geometry. In the sequence of screen captures of Fig. 10, one can see that MR prevents users from selecting any part of the model. As a result, some users resorted to simply holding out the measuring tool and obtaining an approximate dimension. Other users simply became frustrated when they attempted to measure as can be seen in the sequence of Fig. 11. They would attempt to measure a feature but unable to select anything else, a “zero-length” dimension would result. Planar decomposition, as seen in Fig. 12 was the only method from which users were able to obtain dimensions. The frustration of not being able to obtain dimensions from the MR or EN models further illustrates why users determined PD was the best at providing the required information.

In the post-survey, users were also asked to indicate which method they preferred the best. EN and PD had the same number of people (16) who gave positive responses (see Fig. 9b). This is understandable as each



**Figure 9:** Post survey responses



**Figure 10:** MR cannot obtain dimensions

method had more visually accurate geometry and often provided opportunities to make associative references.

The final question of the survey asked for the users' general opinions about using partitioning. There was both a mix of positive and negative opinions. Some key takeaways and representative responses are presented below:

#### Positive

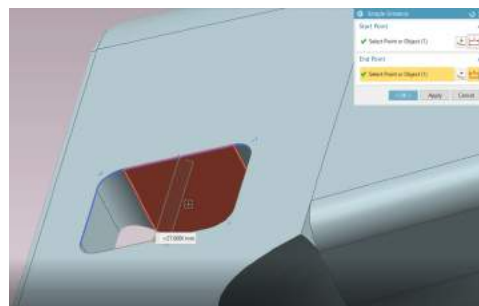
- *"Enjoyed only being able to see the parts of the assembly I needed to work on."* This comment most likely indicates this user enjoyed PD the most as this particular technique hid parts unnecessary to the specific modeling tasks during the tests.
- *"Partitioning is a great idea, it is nice to see the general idea of the part even if we are not supposed to see the real part."* This comment could be relevant to either MR or EN as PD would not allow one to see the whole part.

#### Negative:

- *"I could not grab dimensions from other parts so I did not know how big to model my parts."* This idea was expressed often as a reference to either MR or EN which prevented the user from grabbing and obtaining dimensions.
- *"Hard to interact with the part."* Similar to the previous statements, this likely references either MR or EN which did not allow the user to interact with the part.



**Figure 11:** User cannot obtain dimensions. This was common in most envelope models where the layers were locked, making the geometry inaccessible



**Figure 12:** Planar decomposition makes dimensions available for reference geometry.

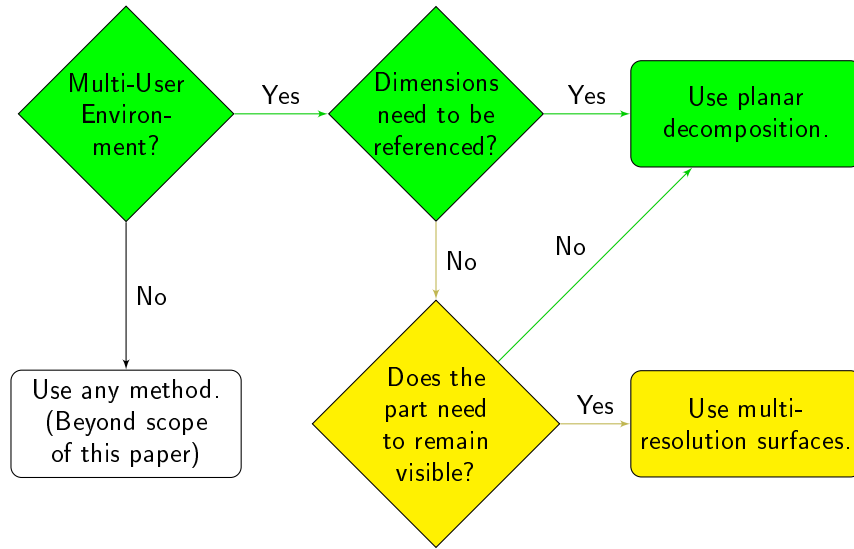
- “*Could not reference geometry well, so it was hard to get things right.*” Similar to the above negative statements, although this may have stemmed from bugs in the research code and simulation, since users were not allowed to enter the child parts (and no one used wave-linking), which removed the option of making planes on part surfaces.

Negative responses came from about 25% of our users who specifically indicated they were frustrated with not being able to reference the geometry and make accurate dimensions. While negative, these responses were to be expected as simulating MR as an STL and EN with locked layers prevented users from referencing any part of the model. In essence, these negative responses are the metrics desired to capture the partitioning methods’ capability of hiding, corrupting, and/or protecting data. On the other hand, the negative responses also indicate that MR and EN were frustrating partitioning methods with which to work and could be detrimental to the primary objective of enabling collaborative work if the partitioning method implemented to protect data is too restrictive.

## 5 CONCLUSION

In order to determine which partitioning method would be most effective in a multi-user CAD environment, the results of the aforementioned tests and surveys were compared against the criteria determined from the literature review. Figure 13 presents a decision-making process illustrating how to choose a partitioning method based on these scenarios.

In addition, two modeling scenarios were kept in mind. The first scenario consists of cases in which a partitioned part needs to be referenced by the party without full access. The second scenario consists of



**Figure 13:** Decision tree for choosing a partitioning method. The path outlined in green indicates the method most likely to be chosen. The path marked in yellow shows the best partitioning method in the unlikely scenario where the part needs to remain visible, but dimensions are not needed.


cases where no references to the partitioned model were needed. According to the test results, decision tree, and the criteria previously described, planar decomposition is recommended as the best method overall to implement in a multi-user CAD system. This recommendation is not solely because it was the favorite in tester surveys since it was tied with EN as the most preferred. Planar decomposition is easy to implement and has some notable key features. For example, placing planes in a CAD environment is easy and highly unlikely to cause potential lags over the network. This is especially favorable as envelope would have to update often if there was a user with access inside the envelope who made changes. Much larger transfers of information would result compared to planar decomposition where no updates are necessary on the cut-off side of the plane. Furthermore, in fulfillment of scenario one, planar decomposition removes unnecessary features from view, leaving only important geometry visible that can be referenced. While this method does not entirely fulfill scenario two, since any geometry shown could be referenced, the placement of the planes allows an administrator to be relatively flexible in the amount of information they want to partition, or hide the part entirely. Lastly, planar decomposition allows users to access the necessary geometry and make associative references, while leaving out information that is proprietary or simply not needed. This resolves one of the biggest complaints user subjects had against partitioning (being unable to reference their geometry). Lastly, a major benefit observed by the proctors was that planar decomposition decreased the amount of distractions created by unnecessary features, which altogether improves the modeling situation, to increase the focus and attention of designers.

Nevertheless, as shown in the decision tree (see Fig. 13), MR is not a partitioning method to discard. Thus a combination of MR and PD to create a new partitioning method is also recommended as a more optimal partitioning option altogether. This is because the reasons MR makes modeling difficult effectively fulfill scenario two where no references to the partitioned part are needed. Users may occasionally need to see geometry to spatially build their part correctly, but no dimensional information about that geometry is necessary and users should be discouraged from obtaining any. As a result, future research into implementing MR as a toggle on/off feature for spatially important geometry within planar decomposition may assist in

pinpointing a partitioning method that fulfills both scenarios.

A more stable platform with fewer bugs would likely improve the experiment's ability to distinguish the differences between frustrations caused by code limitations and frustrations directly related to the partitioning methods. Nevertheless, the authors recognize that useful information was still gleaned from the research code status of NXConnect to determine that planar decomposition is currently the best method to implement in MU CAD with the expectation that future capabilities developed by Siemens directly may alleviate some of these limitations. In the future, modeling experiments with longer time frames could also be beneficial. The short time span provided to the user subjects to model their parts was often not enough for them to fully experience the multi-user environment since time was not afforded to go back and review their modeling accuracy. Lastly, a partitioning test with a planar decomposition and multi-resolution mesh would be insightful to further understand a potentially better partitioning method to implement in multi-user CAD.

## ORCID

John L. Salmon,  <http://orcid.org/0000-0002-8073-3655>

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