6 RESULTS

In this chapter I present some results of the application of our framework for semantic adaptation of large 3D CAD models of Industrial Plants walkthroughs. As a complement, in Chapter 0 some details about the architecture and also about implementation strategies are described.

The results are presented as follows: The first section introduces some realistic examples about potential scenarios where Semantics can improve the visualization experience of industrial plant models. The next section also introduces the methodology for testing the framework. This evaluation schema is divided in two parts. The first part is focused on measuring the effects of a strategy of variation of models, resources, and user purposes and profiles. The second part focuses on evaluating the characteristics of the visualization module, as well as the acceptance of the system by real users performing simple purposes of the Industrial Plant sector.

I present also quantitative and qualitative results coming from the application of the methodology to concrete real-world examples of large Industrial Plant 3D CAD models, with different resources, user profiles and user purposes.

The section 6.4 gives statistical information about the two original CAD models. These statistics are useful to understand better the internal structure of the models and the way in which our semantic framework can treat them to created adapted representations suitable for VR walkthroughs for specific purposes.

These models have been extensively analyzed and studied in Fraunhofer Institute for Computer Graphics (Fraunhofer IGD) in the scope of the research associated to this Ph.D. work.

6.1 Summary of the overall results of this work

I have defined a framework for semantic adaptation of large 3D CAD models of Industrial Plants walkthroughs, which automatically apply and parameterize **different visualization techniques** based on **semantic criteria** in order to produce a custom VR Walkthrough for a specific visualization context, taking into account three main aspects: *user needs and profile, model characteristics, and resources.*

To test the concepts and the framework, I followed a scenario with two different users, two different models and two different resources, and defined an appropriate set of semantic rules. The extended MiroWalk system is now able to display two **complete** representative industrial plant models in a virtual walkthrough environment on current workplace hardware. This was not possible before with a standard convertor between CAD and VR (such as VRLM exporter). Moreover, the VR walkthrough semantically adapts the visualization to specific users; thus, generating different visualization and navigation experiences for different user profiles, model types or available resources. The system is easy to use and hides details about the techniques from the user; the semantic context is simply selected by the user from a list of suggestions. The system is extendable for different scenarios by adding additional semantic rules and symbols.

The **semi-automatic catalog reconstruction tool** finds repeating elements within a MicroStation CAD model and builds a classified parts catalog following semantic criteria**,** thus looking for meaningful groups of geometric objects in the CAD model that correspond to real parts in a typical plant. Subsequently I extended the conversion process from the CAD model to the VR model to exploit the semantic information inherent in repeating parts: I reduce the model's complexity by replacing complex parts with **alternative 3D symbols – semantic synonyms**. I have concentrated on two significant parts of the two example plant models (*Valves and Flanges*) and achieved this way polygon reductions of up to **20%**.

The two plant models (chemical plant, automotive process plant) have **several millions of polygons** when converted to VR using brute-force methods, and were impossible to visualize before in a normal workplace PC within an advanced scene graph system (Open Inventor in our case). With the techniques used in MiroWalk [PLS02], the models could be visualized in real time, and with the use of semantic synonym an increase of performance of **10-30%** could be achieved. This increase of performance is based only on the geometric CAD model and the implicit semantics embedded – no internal links to explicit PIM information were available.

The implemented techniques also preserve an important aspect of the MiroWalk system: the **almost-real-time** response of the system. Within a few minutes a complete walkthrough can be prepared from the conversion of the CAD model to the VR walkthrough environment.

Finally, with the techniques implemented, MiroWalk provides specialized users (engineers, managers, etc.) with a better visual tool for the plant design *visualization purposes*, since the visualization is semantically adapted to their needs.

6.2 Comparison against other Projects and Approaches

I will give a short comparison of the extended MiroWalk System against other projects and approaches that aim, like MiroWalk, on walkthrough rendering of industrial plants or similar engineering models. I will ignore rendering systems for other specific domains like terrains or architectural models – as MiroWalk was not designed for such models it will unlikely perform better than systems that take advantage of the special features of these models.

Compared to high-end walkthrough systems MiroWalk still plays in a different league regarding performance – though also with respect to the hardware requirements. For displaying its Double Eagle Tanker Model, for example, the Gigawalk system [BSG02] needs more than 35 hours of conversion time and one gigabyte of main memory resulting in an eight gigabyte VR-model. To display this model a SGI Onyx workstation with 16 gigabyte main memory, three CPUs and two graphics pipelines are used [BSG02]. Compared to this, the MiroWalk setup and requirements appear fairly modest, even though comparing such different systems directly may not be perfectly appropriate: the model is neither a Plant Design model, nor does it focus on semantic aspects; it has different hardware requirements and therefore a different order of magnitude in number of triangles, etc.

In the conversion process, MiroWalk took advantage of cell and layer structures of the CAD model. Work like [SBM01] showed that recreating this structure is possible, but increases the preprocessing time and does not necessarily lead to semantically logical entities.

As stated in [ACW98] a single algorithm might provide a performance increase over naive rendering, but when two algorithms are combined they do not necessarily achieve their combined speed-up. Therefore, an interesting aspect when comparing MiroWalk to other systems is that other approaches are usually orthogonal to our semantic approach. It is indeed reasonable to combine other sophisticated techniques like image-based rendering, occlusion culling, etc. in conjunction with our control by semantic criteria.

For instance, when comparing MiroWalk to the experimental system by Nuyden presented in [NUYD02], on the first sight the MiroWalk seems to be inferior in performance. Nuyden's work can display the thirteen million triangles heavy power plant on the same setup as ours. But again, Nuyden's approach is clearly complementary to the MiroWalk approach, and *does not include any semantic improvement* of the visualization. Indeed combining the use of pure hardware occlusion culling (the basis of Nuyden´s performance) and MiroWalk's semantic conversion should be possible and a combined system would surely benefit from both approaches.

The Large Model Viewer bundled with TGS Open Inventor can neither display the non-optimized plant example models nor the plant models that were optimized by MiroWalk. This is especially interesting, since the MiroWalk viewer itself is based on the general purpose TGS Open Inventor viewer module – without large model optimizations. This leads to the surprising conclusion that the Open Inventor optimizations in our case are rather hindering. This may be directly related to the fact that a combination of multiple optimization techniques leads to a CPU overhead in structuring the scene-graph.

When MiroWalk is compared to commercial projects like PlantSpace Review [INTG05] and AutoPlant Explorer [BEN05], the fundamental difference between both systems is the basis they have to work on: PlantSpace Review and AutoPlant Explorer have access to underlying PDM information and are integrated into a plant design system. In contrast the only data MiroWalk has as input is the geometric CAD model and its implicit semantics. Hence, MiroWalk is more generic in its approach. The achieved performance is nevertheless comparable. Besides, MiroWalk offers a specially adapted representation for each user profile and purpose, something that is not available in those products.

6.3 Scenarios where Semantics can improve the Visualization

In this section I present some realistic example scenarios that show the potential effects of varying the three elements of the *semantic triangle*, and to make more evident that the walkthrough in VR of Industrial plant models should take into account these elements:

- *User purpose and profile*
- *Resources*
- *Model*

The examples are mainly illustrative, the actual variations on user, resources and models used for the tests will be explained in the next section.

6.3.1 Example with different User Profiles

A small sized engineering company has accepted an order from a large pharmacy company to retrofit their existing chemical plant to match the requirements for their new product. To make the changes fit the existing part of the building, the company provided CAD data exported from their PDM system. **An engineer** has already finished his part of the work: a new hall attached to the existing building and some modifications to the old building. He wants to do a final review before passing the data on to the contractor. From previous experience he knows that a critical part is the piping system, a vast net of pipes that goes through the whole building. Especially the connections of the old and the new parts are critical locations. The engineer knows about products like AutoPlant's clashdetector, but either his company cannot afford to buy it or he does not fully trust the product and wants to double check with his own eyes.

He knows a virtual walkthrough would give him a natural view of the construction site as a construction worker would see it. Design flaws often catch the eye more easily while virtually walking through the building. Unfortunately, he only has his workstation available since the company is too small to afford high-end visualization systems.

Normally his workstation would be too slow to display a VR view of his complex model. However, his semantic export system knows **the context of his intention and his abilities** and creates a custom model that fits his purpose. The system knows that the complexity of the model must be reduced and so decides to apply several optimizations that will not affect his intention. Just displaying the piping system alone would reduce the complexity, but is in this case not feasible, since the engineer is particularly interested in interaction of the piping parts and other parts of the model that may be in its way. Instead, the system knows that the viewer is not interested in detailed renderings of the many valves, boilers and other parts and decides to replace them with **3D symbols** that have about the same extents but are much less complex to render. For the engineer no information is lost, since he knows these symbols already from his day-to-day work. The model is now reduced in complexity so that it can be rendered on the engineer's workstation. Additionally, the export system displays all parts of the piping-system in a highlighted color to support the intention of the engineer. Indeed the engineer quickly finds a pipe that goes right through a wall in a location where no hole exists.

Later that day the same engineer has to prepare a presentation for some investors that may be interested to provide some funding for this company. Since **none of the visitors has engineering background**, presenting 2D CAD views of their work does not make sense. Thus, he decides to produce a walkthrough demonstration in a virtual environment. This time the export system – aware of the changed context – decides to achieve the desired reduction of complexity in a different way. To reduce the complexity it simply replaces all valves with simple pipe sections and also blends out other details that cannot be understood by the visitors or would even confuse them. The potential investors still see a complex network of pipes and are impressed by the company's know-how.

6.3.2 Example with different Models

The same engineering company does not just get orders from the chemical industry, but is also related to the automotive industry; they currently have a contract for developing the plans for a new process plant and have scheduled a presentation to the leading board. Again, visualizing this plant in a walkthrough environment pushes the company's visualization capabilities to their limits. The semantic visualization system is aware that **a**

process plant has a different nature than a chemical plant and thus knows that a different optimization strategy is needed. To reduce the complexity of the model, the export system hides almost the whole HVAC system of the process plant model. This does not affect the visual quality in this case, since the HVAC is almost completely hidden in the buildings ceilings and not visible during a virtual walkthrough on the plant's ground floor.

6.3.3 Example with different resources

Impressed by the results of displaying their plant models in virtual walkthrough environment the company invested in a new special set-up for tests (which includes a bigger screen and a space ball as interaction device). While creating the VR-Model the semantic visualization system now has **two target hardware setups**: the engineer's workplace computer and the new set-up. **Aware of the different resources** the semantic visualization system knows the maximum model complexity displayable by the selected hardware and can create a suitable model. The company is also interested in investing in the future in a large screen projection system for this purpose. The system would also adapt accordingly.

6.4 The test datasets: two real world models of Industrial Plants

The concept of multiple users, models and resources is central to our work. Thus should our implementation always consider at least two of either of these (two models, two users or two resources).

Analogously to the scenarios of previous section, I use **two complex real-world CAD models** from two different engineering domains as test cases for our work:

- A large industrial process plant
- A large industrial plant from the chemical industry.

Both plants have a different general structure, are composed of different parts, and need a different strategy for optimization. The next section will describe in detail the properties of these two models.

In the same way I use the **two typical user profiles** described in the above scenarios:

- A general engineer
- A manager

A user with an engineering background has a profound knowledge of the technical aspects of the plant design process. He knows common terminology and symbols of the plant design world and has a more technical/conceptual perception of the model. Additionally an engineer usually has a focus of interest when viewing the model. The scenarios showed that we can optimize the quality of the visualization by following a strategy that takes advantage of the semantic information of the engineer to create a less detailed, more conceptual or symbolic representation of the plant models. In contrast a user with **a manager profile** misses the profound understanding of the technical aspects. He has a more general perception of the model. Thus, a different optimization strategy will be used: detailed technical aspects may be simplified or completely hidden. However, parts that have a huge impact on the general visual appearance should be rendered in high quality.

To test our work on two resources I have setup **two computer-systems**: An up-to-date workplace computer with a graphics card of the newest generation, and a less powerful computer-system with less main memory and an older graphics card. During our work MiroWalk will be tested regularly on both resources and also the final measurements will be done on both systems. The hardware specifications are the following:

- System 1: PC Intel Pentium 4 CPU 2,4 Ghz / 512MB RAM

  Graphic Card : NVIDIA GeForce 4 Ti 4200 with AGP8X

  Screen: SyncMaster 915N - 19" - 1280x1024

  Space Ball - 3D connection

- System 2: PC Intel Pentium 4 CPU 1,4Ghz / 256MB RAM

  Graphic Card: NVIDIA Riva TNT2 Model 64 Pro

  Screen: SyncMaster 730B - 17" -1280x1024,

  Mouse

6.4.1 Statistics of the models: Industrial Plant and Process Plant

As sample models I used two complex CAD models from two different Industrial Plants: a large process plant of a German producer described in [PWTS04a] and a plant from the chemical industry. Both models are real-word examples and could not bet visualized without problems using the available tools on the market. Also they were still a problem for the first MiroWalk implementation; only subsets of the model could be visualized. Complete views of the plants could only be visualized with radical simplifications that led to a relatively poor quality.

The chemical plant is a huge three-story building with a concrete skeleton as main supporting construction that carries the concrete floors (Figure 67). The building halls are filled with a complex piping system spanning three stories and also reaching into the outside environment. Attached to the piping system are numerous boilers, valves, barrels, mounting material, pressure gauges, etc. Especially the piping system and its attached parts contain a lot of curved elements that appear costly to render.

The process plant is a wide one-story building with a metal framework construction as its main supportive structure with several thousands of metal beams (Figure 68). The building is equipped with a lot of heating, ventilation and air conditioning equipment (HVAC) and has a sprinkler installation covering the whole building. If visualized in 3D, the halls of the plant appear rather vacant since the processing machinery is not yet installed and the HVAC etc. are hidden in the roof behind a covering ceiling. Because of this, in a VR environment the model's complexity is not obvious at first sight.

The provided tools for MicroStation and Open Inventor were not powerful enough to get statistics as detailed as needed. I used a special application to *selectively export* subsets of the models.

The models were already divided *into levels* in a more or less logic way. I did a testing application able to select the exported subsets on a finer granularity. This made it possible, for example, to selectively export all NURBS objects, all cylinders objects or just the plain triangles. The following parameters could be set in MiroWalk to specify the subset that should be exported:

- Skip specific primitives based on its type
- Set the complexity parameter discretely for NURBS and some solid primitives
- Export only selected levels,
- Export only manually selected elements.

The *ivperf.exe* program of Open Inventor is a tool to measure frame rates and triangle counts of VRML models. It was used to measure the exact number of triangles of the exported subsets.

6.4.1.1 Statistics for the Chemical Plant

The distribution of triangle-producing elements of the chemical plant was quite astonishing. About **60%** of the triangles are produced in two distinct levels of the model. These levels contain all parts of the piping systems: valves, flanges, elbows, t-adapters, etc. The pipes themselves are not part of these levels. These elements are about 1500 small repeating disjunctive elements organized into cells and are composed of only one to seven geometric primitives per element, mostly cones and NURBS (see Figure 66). Analyzing the levels manually shows that the 1500 elements are of about 50 different types of elements in different positions, scales and orientations. Just the valves of the model make up for **18%** of all model triangles; the elbows consume about 10%.

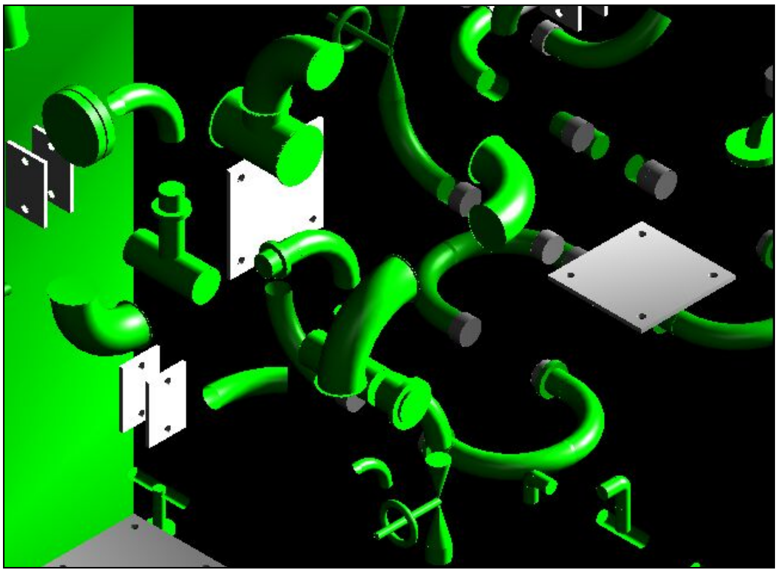


Figure 66. Some elements of chemical plant – many triangles for few information. Redundancy is high.

About **10%** of the triangles result from round pipe elements made of cylinders that are spread over four levels. These pipes usually connect the parts found in level 10 and level 12. Boundary representations of flat faces only produce less than **4%** of the overall triangles, even though they have a huge impact on visualization, since they are usually a part of big structures like columns, floors, the roof, etc.

Looking at the geometry not organized into cells, I estimate that another **10%** of the triangles come from about 100 complex objects in level 10. These are boilers and tanks composed of primitive geometry, but that are not grouped together as cells (Figure 67).

Less than 3% of the triangles are part of other repeating element like columns, windows, square pipes, etc.

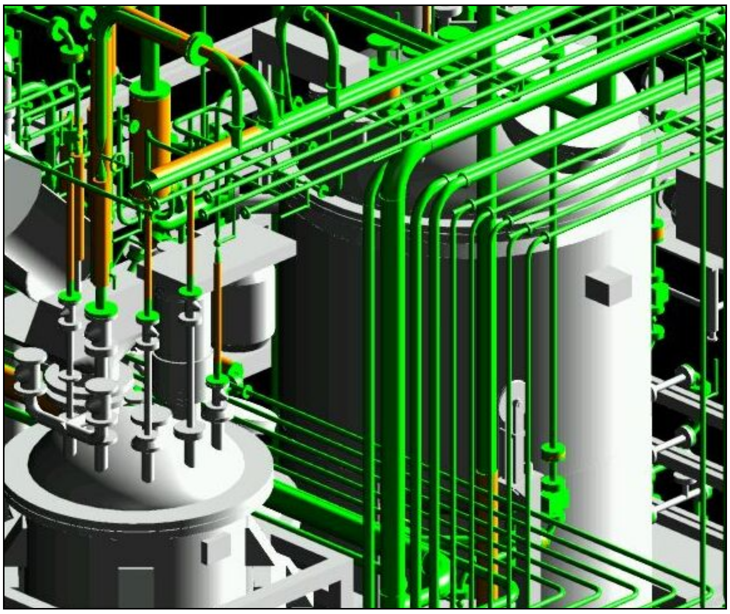


Figure 67. Chemical Plant – Screenshot . Complex piping systems are critical for visualization

The small-cell LOD (set to the default size threshold of 0.3 units) that displays elements below a certain size and distance to the viewer as a bounding box leads to an improvement of about **22%** of total triangles. Displaying the complete model with MiroWalk is only possible with an unacceptable loss of details when setting the Open Inventor complexity parameter to extreme values below 0.1.

6.4.1.2 Statistics for the Process Plant

Looking at the process plant model the results were not quite as clear, but still obvious "hot-spots" of triangles could be found. Even though this model appears when seen rendered in 3D subjectively much simpler than the chemistry plant, it is actually more complex since it features a wider variety of structures.

A major hot-spot becomes more apparent if I define a virtual pipe group composed of twelve levels of the model that contains all parts related to the models HVAC. About **50% of the model's total triangles** are a product of the pipe group levels. The NURBS objects in this pipe group create **about 28% of the total triangles**. These NURBS objects are curved parts of the piping system organized into cells. The majority of these parts are pipe elbows and some valves. The cylinders in the pipe group produce **about 19% of the total triangles**. These 19% can be reduced to 11% by the cylinder/box optimization.

Another 7% of the total triangles are a result of level 12. About 3% result from repeating columns and 4% by the roof lattice made of a metal cross-beam structure (Figure 68). The roof's cross-beam structure is constructed of repeated elements but is not organized into cells.

The sprinkler heads of the sprinkler system in level 51 and partly in level 62 produce about 7% of the model's total triangles. The 1982 sprinkler heads are organized into one cell per sprinkler head. During the export the cell is mapped to one cone and one NURBS object and produces 72 triangles. The sprinkler heads are very small and have low visual influence on the overall appearance of the VR scene.

About 15% of the total triangles are taken by carrier-beams of the roof in level 26. These beams have a cubic form, but are unnecessarily represented by B-Spline boundaries, which lead to this high triangle count. A similar situation can be found in level 57 where 3% of the model's total triangles are caused by 120 flat metal beams constructed of B-Splines.

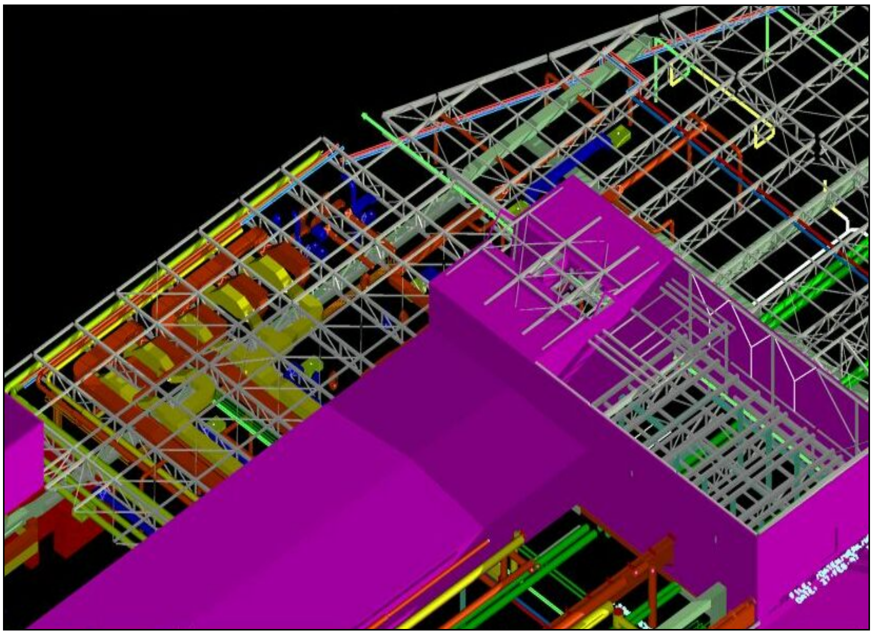


Figure 68. Cross-Beam Structure of Roof of Process Plant – Second model used for MiroWalk results

Table 10 to Table 13 show the initial statistics of both models, according to the classification of primitives in the underlying 3DCAD system

Table 10. Statistics Chemical Plant – type of components– Initial categorization based on visual inspection (not STEP-categorized)

Levels	**Content**	**Triangles**	**NURBS**	**Cyl Prim.**
1	Wires	5%	2003	0
2	Pipe Parts	40%	8642	8590
3	Green Pipes	5.3%	92	3416
4&14	Bronze Pipes	1.2%	0	880
5	Yellow Valves	1.2%	12	795
9	Metal Anchors	.	.	.
10	Ducts, Tanks	11%	1084	2740
11	Ducts	0.1%	.	.
12	Pipe Parts	21%	1634	7644
13	Green Pipes	3%	0	1921
15	Walls & Valves	0.9%	0	449
16	Windows	.	.	.
20	Stairs	0.1%	0	0
21	Windows	0.3%	.	.
22	Floors	.	.	.
25	Concr. Skeleton	.	0	0
31	Green Plates	.	.	.
35	A Blue Plane	.	.	.
39	Blue Fences	.	.	.
48	Marker	.	.	.
50	Marker	.	.	.
51	Clamps	4%	691	437
61	Coord. System	.	.	.

Table 11. Statistics Chemical Plant – Concentration of HVAC & Piping components

Levels in CAD Model	**Type of elements contained**	**Tris**	**NURBS**	**Cyl. Prim.**
3,4,13,14	HVAC & Pipe Group	9%	92	5176
2,12	HVAC & Pipe loose components	61%	10276	16234
Other levels	Other elements in Industrial Plant	30 %	14446	27081

The Table 12 and Table 13 show similar statistics for the Process Plant. Notice also the high concentration of special elements in certain levels.

Table 12. Statistics Process Plant – type of components–Initial categorization based on visual inspection (not on STEP)

Levels	**Content**	**Triangles**	**NURBS**	**Cyl Prim.**
1	Vent Pipes	1%	87	15
2	Vent Pipes	4%	947	15
3	Vent Pipes	2%	517	0
4	Vent Exhaust	1%	51	288
5	Pipe	1%	136	0
7	Trees	.	63	0
10	Walls	1%	141	0
11	Beams	1%	68	89
12	Roof	7%	62	1
13	Walls	.	0	0
19	Pipes	1%	90	192
20	Street	1%	442	0
21	Windows	1%	88	0
22	Connections	1%	72	0
26	Roof	15%	1710	0
27	Roof	.	270	0
28	Wires	.	0	0
30	Flat Pipe	.	6	0
31	Vent Pipe	5%	299	311
32	Vent Pipe	4%	174	412
33	Big Part	1%	71	0
35	Big Block Parts	.	0	24
40	Small Block Part	.	0	0
51	Sprinkler Heads	6%	1768	0
53	Stairs	1%	142	0
57	T-Carriers	3%	116	0
58	Pipes	29%	4051	6102
59	Pipes	3%	0	1424
60	Real Estate	.	0	0
61	Block Part	.	3	3
62	Building Struct.	7%	4031	2

Table 13. Statistics Process Plant – Concentration of HVAC & Piping components

Levels in CAD Model	Type of elements contained	Tris
59, 58, 31, 32 **1, 2, 3, 5, 19**	HVAC & Pipe Group	50 %
Other levels	Other elements in Industrial Plant	50 %

6.5 Results of the test on two models in different resources

Table 14 and Table 15 show before/after measurements of the rendering performance and the number of triangles for both models on the first of our two computer systems. I converted the two example models, first non-optimized and then optimized for the user profile **engineer** and also for the user profile **manager**. I then measured the number of triangles and the performance in frames per second.

For the chemical model I got for both user profiles a **triangle decrease of approximately 30%** and a **performance increase of approximately 50%**. The subjective visual quality, however, remained at the same level in both cases.

The file size was generally compressed by 30-50% due to the export of repeated elements as shared elements. This effect is not noticed in the performance or the number of triangles though, because TGS Open Inventor "unpacks" the repeated elements into the scene-graph and creates a new node for every repeated instance.

One thing I noticed is that the results for the chemical plants are better than the results for the process plant. I measured a performance increase of 20-50% for the chemical plant while for the process plant only an increase of 6-16% was measured. This can be explained through the nature of the models.

Even though the process plant has a lot more elements, in general a smaller percentage of them are organized in cells (see Table 14). Due to the fact that our algorithm only accepts cells as repeated elements, the chemical plant is obviously more suitable, because 65% of all elements are part of a cell. In contrast only 20% of the process plant elements are part of a cell. Thus, the chemical plant should benefit more from our optimizations which is in deed directly reflected in the performance and compression rates I measured.

The MiroWalk performance was also measured on a second, slower computer system. I created a subset of the chemical plant model that only contains the piping system, because the hardware was not strong enough to display the entire model. Table 14 shows the results of the performance measurement on the slower hardware system. The chemical plant piping subset contains mainly the elements that I concentrated our optimization efforts on (valves, elbows, etc.). Thus, the results for the chemical plant subset expressed in percentages are slightly better than the results measured on the first computer system for the complete model.

6.5.1 Measurements in terms of performance / Techniques

In Table 14 the initial situation is presented. It shows the results obtained by MiroWalk doing a conversion with all optimization techniques turned off. User profiles were not considered during this phase.

Table 14. Original situation with brute force tessellation

	Triangles	**Fps Computer 1**	**Fps Computer 2**	**File Size**	**Unstructured groups**
Chemical Plant big section	3,45M	2.07	-	29.7 MB	13147
Process Plant big section	2,69M	2.75	-	45.0 MB	9224
Chemical Plant small section	1M	-	1.13	-	-

In order to see the effect of the implemented optimization techniques controlled by semantics, I applied during the conversion some of the techniques described in Chapter 5.4, in particular the following:

- The semiautomatic reconstruction of some important conceptual components(catalog)
- The application of a concrete NURBS tessellation complexity on a per-part basis, based on the importance of objects for different user profiles.
- Intensive use of the semantic synonyms technique that keep the full meaning expected by the user.

This subset of techniques is directly related to the ontologies introduced in Chapter 5.3 and serves as a proof of concept of the impact of semantically steered techniques in our context. I have focused the measurements on these three techniques; the other methods are complementary and may lead to additional improvements.

The Table 15 and Table 16 show the improvement of performance comparing the initial situation and the results obtained with the addition of semantic criteria to control the techniques:

Table 15. Percentage of improvement with semantic adaptation for walkthroughs.

	Reduction In Triangles	**Increase Fps Computer 1**	**Increase Fps Computer 2**	**Reduction File Size**	**Reduction Unstructured groups**
Chemical Plant Big Section					
Engineer	52.4%	198.0%	-	58.6 %	18.5 %
Manager	57.1%	210.6%	-	58.2 %	18.5 %
Process Plant Big section					
Engineer	54.6%	180.0%	-	75.5 %	52.9 %
Manager	56.5%	175.2%	-	75.5%	52.9%
Chemical Plant Small Section					
Engineer	58.0%	-	205.3%	-	-
Manager	54.0%	-	223.0%	-	-

In Table 16 the results for the structuring and internal classification of the objects into concepts of the ontology are presented, an important basis for the improvement in performance.

After a thorough analysis of the model I found out that more than **65%** of the triangles (even after the use of pure geometric LOD) were produced in the piping system substructure. This high proportion (60-80%) is preserved also in other models I have tested. I have therefore concentrated our efforts in this subsystem, and the techniques used for semiautomatic detection, adaptation to the ISO-STEP 10303 standard, and semantic compression representation, are focused on the typical components of this subsystem: valves, flanges, elbows, pipe sections, piping clamps, T-adaptors, sprinkler heads, etc.

Table 16. Effectiveness of the classification for both models

	Chemical Plant		**Process Plant**	
Initial Unstructured Groups	13147	100%	9224	100%
Valves	867	7%	157	2%
Elbows	2064	16%	1248	14%
Flanges	3663	28%	0	0%
Pipe Section	3509	27%	31	0%
T-Adaptors	425	3%	878	10%
Sprinkler Heads	0	0%	1982	21%
Clamps	191	1%	0	0%
Groups not identified	2428	18%	4879	53%

With regard to the Catalog Reconstruction Module, it is interesting to see how the elements in this concrete model were grouped. Table 17 shows this distribution

Table 17. Distribution of Elements in the Model

	Chemical Plant		**Process Plant**	
Total Elements	99799	100%	153639	100%
Elements within Cells	64520	65%	30784	20%
Number of Cells	13147	100%	9224	100%
Number of Cell families	1104	8%	1376	15%
Instantiated Cells	12043	92%	7835	78%

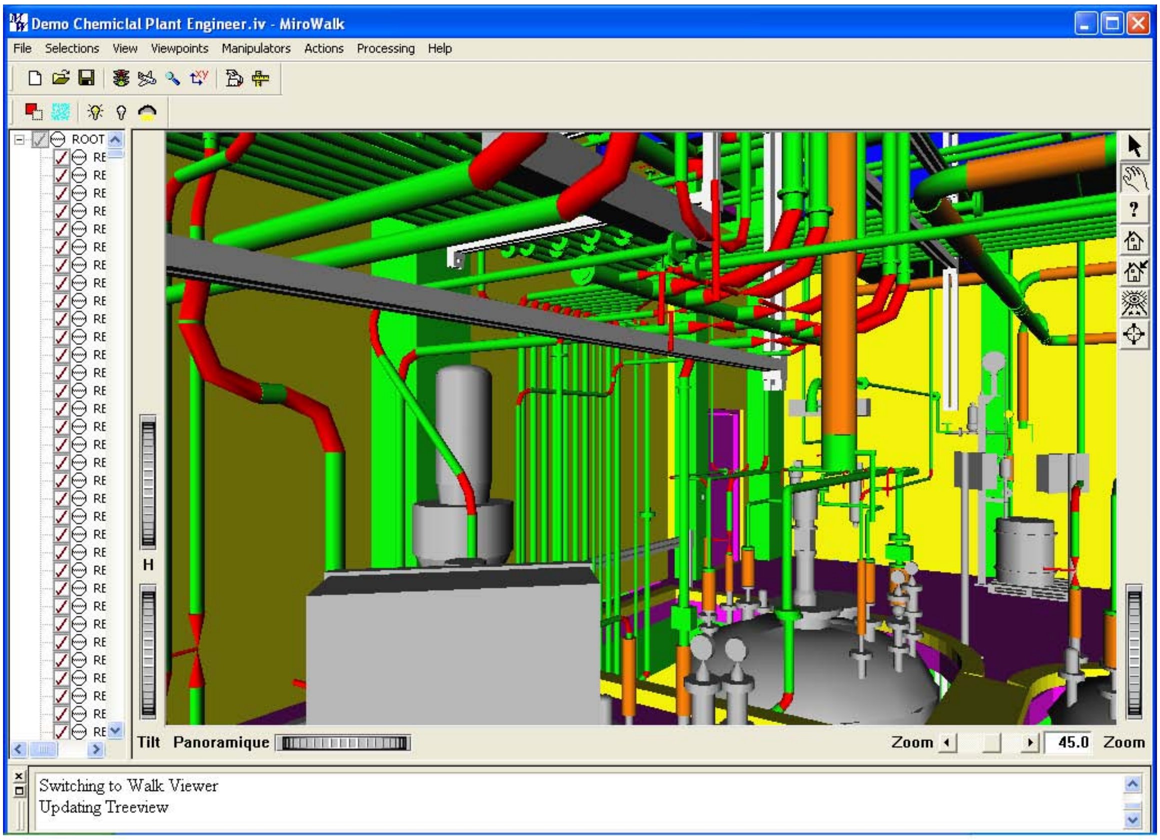
Table 16 shows that a high proportion of the total of primitive elements in the model is indeed grouped in cells (**65%**). This accounts also for a high proportion of the total number of triangles rendered (about 87% of the triangles, even using geometric LOD with complexity = 0.3). From the geometry not organized into cells, another 10% of the triangles come from about 100 complex objects -boilers and tanks- and 3% of the triangles are part of other repeating element like columns, windows, square pipes, etc.

The *Catalog Reconstruction Module* (Chapter 5.1) was able to classify the 13147 cells in 1104 families with the Cell Matching algorithm.

Table 17 shows that actually a large number of cells belongs to a few cell families of the ISO-STEP 10303/AP227 standard; the rest (unknown) are relatively sparse but are not very relevant in relative weight for the final result. This means that the *ISO-STEP 10303 Adaptation Module* (Chapter 5.2) was able to classify **82%** of the total cell families and relate them to the standard.

6.5.2 Detailed results for semantic steered techniques in the chemical Plant

I present in this chapter the results of using our framework in a real-world chemical plant model. The model was generated in a professional Plant Design system, whose 3D CAD geometric representation was used as the basis for the Design Review walkthroughs. It is a large three-story building with a structural skeleton as main supporting construction. The building halls are filled with a complex piping system spanning the three stories and also reaching into the outside environment. Attached to the piping system are numerous flanges, boilers, valves, tanks, fittings, pressure gauges, etc. Especially the piping system and its attached parts contain a lot of curved elements that are very costly to render.



```
Switching to Walk Viewer
Updating Treeview
```

Figure 69. Semantic synonyms in the Chemical Plant model (shown as red parts). Geometry is simplified

Table 18 shows the effect of the Semantic Adaptation Module (5.4.) and the Adaptive Representation Module (5.5.) per part type. The results shown are for a piping engineer as user, with a *check connections* purpose.

Table 18. Effect of semantic compression for some parts in the Chemical Plant model.

Component / # tris	**ISO –STEP Valve**	**ISO –STEP Elbow**	**ISO -STEP Flange**	**Piping Clamp**
# of tris (pure geometric, high quality tessellation complexity = 1.0)	48710	6080	5888	19378
Pure Geometric LOD. # of tris (not semantically compressed). Complexity = 0.3	1302	204	121	594
Semantic compression representation # of tris. User: *Engineer* Resources: *Pentium IV, GForce4, 512MB RAM*	100	32	80	0 *
Ratio semantic rep. vs. geometric LOD	7.68 %	15.6 %	66.1 %	0 *

It is evident from the table that a brute-force, blind conversion with very high quality from the original CAD geometry would create an untraceable model in the practice for design review. Just the valves would create several million triangles. Therefore I take as basis for our comparisons a model already including several simplifications, especially the use of geometric LOD on the original CAD geometry with a complexity of 0.3. This complexity factor in our system is a parameter between 0.0 and 1.0, where 1.0 is the highest accuracy representation (for instance, for NURBS primitives tessellation, it specifies the relative deviation with respect to a predefined threshold). I estimate that a value under 0.3 would create distortions on the tessellated model too evident for the user.

It can be seen that the use of this technique (geometric LODs) brings a high reduction on the number of triangles generated. This and other computer graphics techniques are the basis of common walkthrough systems (culling, pre-fetching, impostors, scheduling, etc.). I bring an additional improvement to these traditional techniques by introducing semantic parametric representations, based on the knowledge of the domain and the related standards, bringing an even better improvement factor, as shown in the table. The element with the highest reduction (valve), for example, is represented semantically with just 7,68% of the best geometric LOD simplified object. In the case of the clamps, however, the semantic criterion gives an even better hint: the clamps are just *not shown* (drop culling technique) for this specific purpose and user.

In the Table 19 we can see the effect of the semantic compression taking into account the number of instances of each part type in the model.

Table 19. Semantic compression reduction

PART	ISO -STEP Valve	ISO - STEP Elbow	ISO - STEP Flange	Piping Clamp
Instances identified in the model	867	2064	3663	191
Total # of triangles of all parts (Pure Geometric LOD)	1128 K	421 K	443 K	113 K
Total # of tris of all parts (with semantic compression)	87 K	66 K	293 K	0 *
Semantic compression reduction (compared to pure geometric LOD)	**92 %**	**84 %**	**33 %**	**INF**

Thus, the semantic compression improves in several cases more than 80%-90% the purely geometric simplification approach, and this especially in those components with highest weight in tessellated model.

The tessellated model of a representative section using only geometric LOD plus some culling / fetching techniques gave an average number of triangles of 3450 Ktris, with a complexity of 0.3 (this is already a very good simplification factor). However, applying the semantic compression model, I could reduce the model in additional 1659 Ktris, for a **net reduction of 51%** in the total number of triangles between the semantically compressed model with respect to the geometric LOD simplified model.

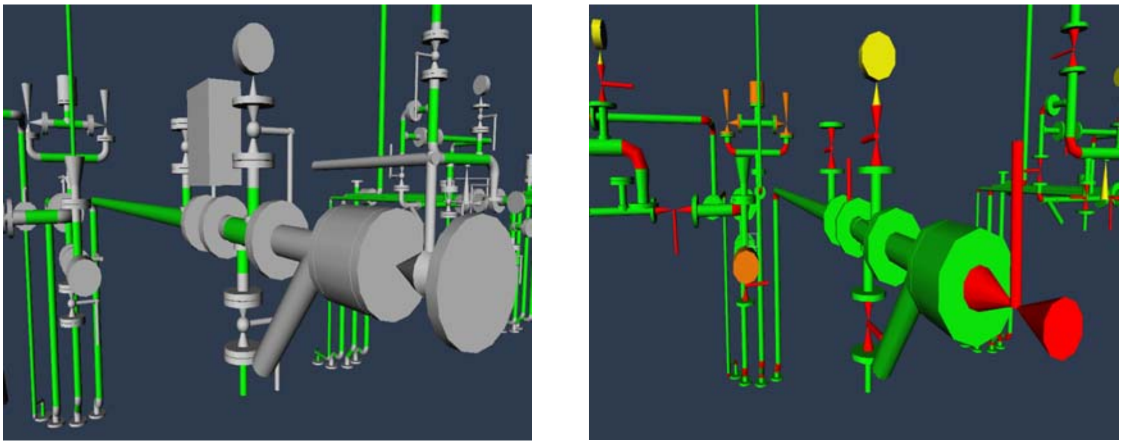


Figure 70. A view of the piping subsystem (Left: geometric LODs. Right: semantic compression representations for elements associated to ISO-STEP 10303-AP227)

Figure 70 shows two screenshots of the model with geometric LOD simplification vs. semantic compression representation.

6.5.3 Conversion Time

The time for the conversion from the CAD model to the VR model increases significantly if semantic optimizations are used. This is mainly due to the time needed for matching each cell of the model to the templates of the catalog. However, export times of around ten minutes are still acceptable for **near-real-time conversion**. Ten minutes preparation time is especially low compared to preprocessing times of other visualization system that reach multiple hours and days [BSG02]. Using some kind of hashing algorithm the conversion time could be further reduced.

Table 20. Preprocessing Times

Model	***Export - no Optimization***	***Export with Engineer Optimization***	***Reconstruct Catalog***
Chemical Plant	28 seconds	11:45 minutes	11:22 minutes
Process Plant	1:27 minutes	5:26 minutes	5:29 minutes

It is no coincidence that the time needed for reconstructing a catalog and for exporting the model are about the same: for both each cell of the model has to be matched against all catalog templates.

6.6 Analysis of the Results

The tables show the influence of the semantically steered techniques on the performance of the walkthroughs. Instead of comparing the performance of our system to other systems, I focus on showing the potential increase of performance of most traditional LMV systems by introducing similar techniques as the ones presented here.

With respect to the influence of the user profile, we see that the overall performance increases for both profiles (*engineer / manager*) in all the measured aspects. The number of triangles is reduced for both models to about 50% - 60%. The frames per second are in both cases reduced close to twice the original fps, as it could be expected, even considering the small overhead in the structuring. On the other hand, the file size (an important factor for storage and collaborative work) decreased to about 50% in the chemical plant, and to 75% in the process plant. The reduction is due to the non-redundant storage of structured groups.

Finally, the Table 16 shows how the majority of unstructured groups of geometric primitives in both models could be tackled in a high proportion with the use of the ontologies described in Chapter 5.3. In the chemical plant, **81.5%** of all the unidentified groups could be classified (and therefore, adapted to the semantically steered techniques), whereas in the process plant, **52.9 %** of the groups were identified. The difference is due to the fact that the chemical plant is composed of many parts/components that are part of the ontology, while the process plant has several elements that are not yet included.

Based on the above results, we can say that the identification of a small subset of concepts related to physical components often used in Plant Design, and the use of techniques that take advantage of the explicit definition of rules for user profiles, available resources and model types, can bring important improvements in the performance of walkthroughs for Plant Design. This is especially applicable to common workplace PCs and near-real-time conversion times.

In general, our work significantly improves the performance of interactive walkthroughs in our example models. Now it is possible to visualize both models at interactive frame rates showing an adequate visual quality (Figure 77 and Figure 79).

6.7 Examples from Adapted Visualization Walkthroughs

The following pages present a selection of our results as annotated screenshots to give the reader an impression of the visual walkthrough adapted for different models, resources, users and purposes. In all cases interactive rates for the walkthroughs were possible. In many cases this was not possible before, using only brute force tessellation.

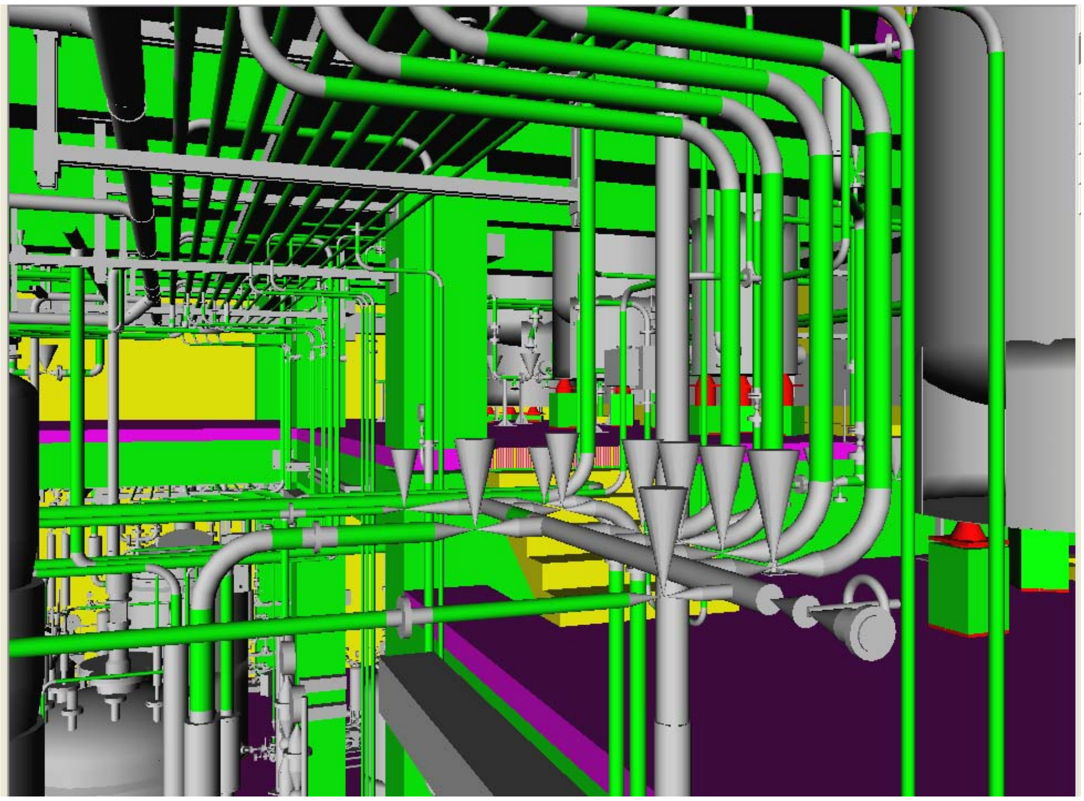


Figure 71. Details of the piping substructure in the chemical plant model for a Piping Engineer in Design Review. Grey parts are of interest for this user. These parts are brute-force tessellated in a PC with good graphic & memory resources.

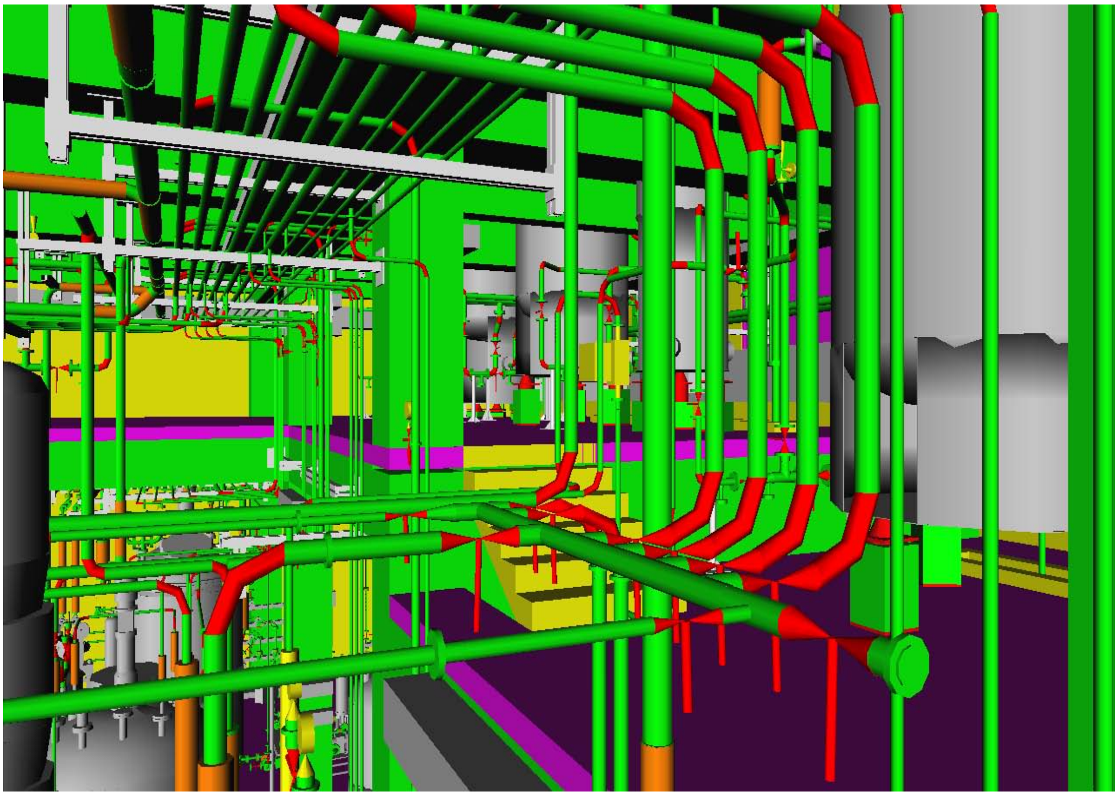


Figure 72. Automatic semantic adaptation of elbows and valves (in red) for piping engineer. Purpose: Design Review. PC of limited resources. High *fsem* and medium *fges*.

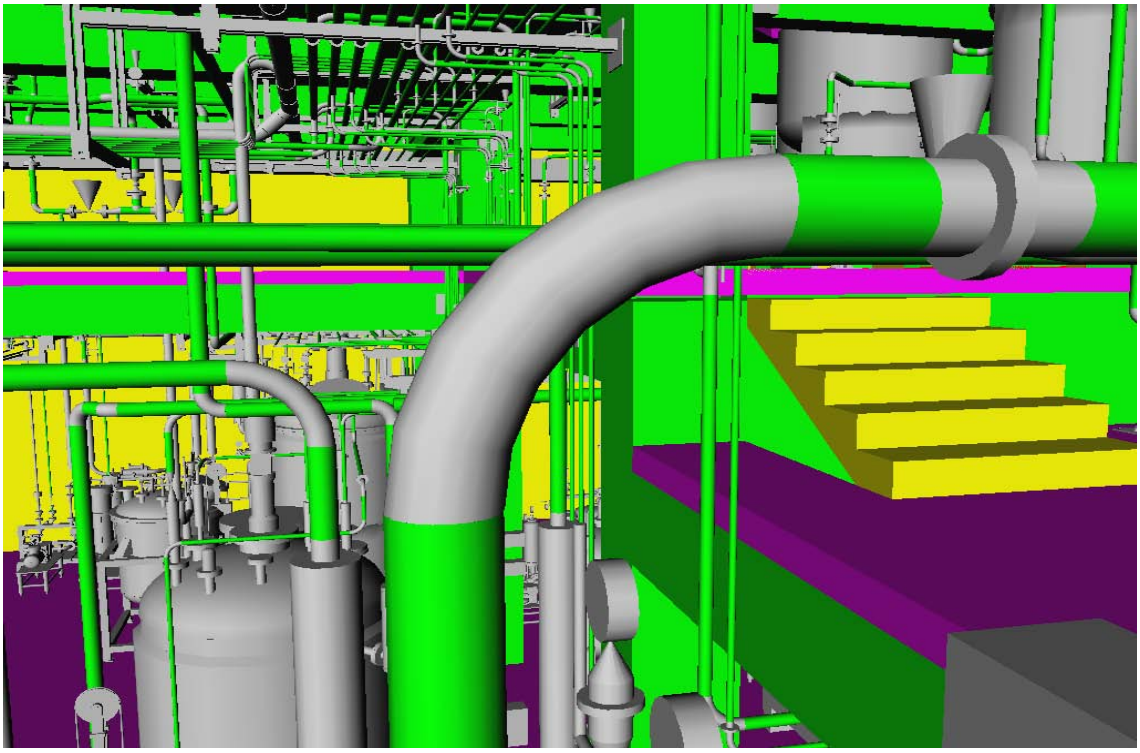


Figure 73. Detail on object-space semantic simplification. The elbow in this figure is recognized as an ISO-STEP elbow (COD. 4.2.66), and rendered in full detail for a piping engineer in a collision detection purpose.

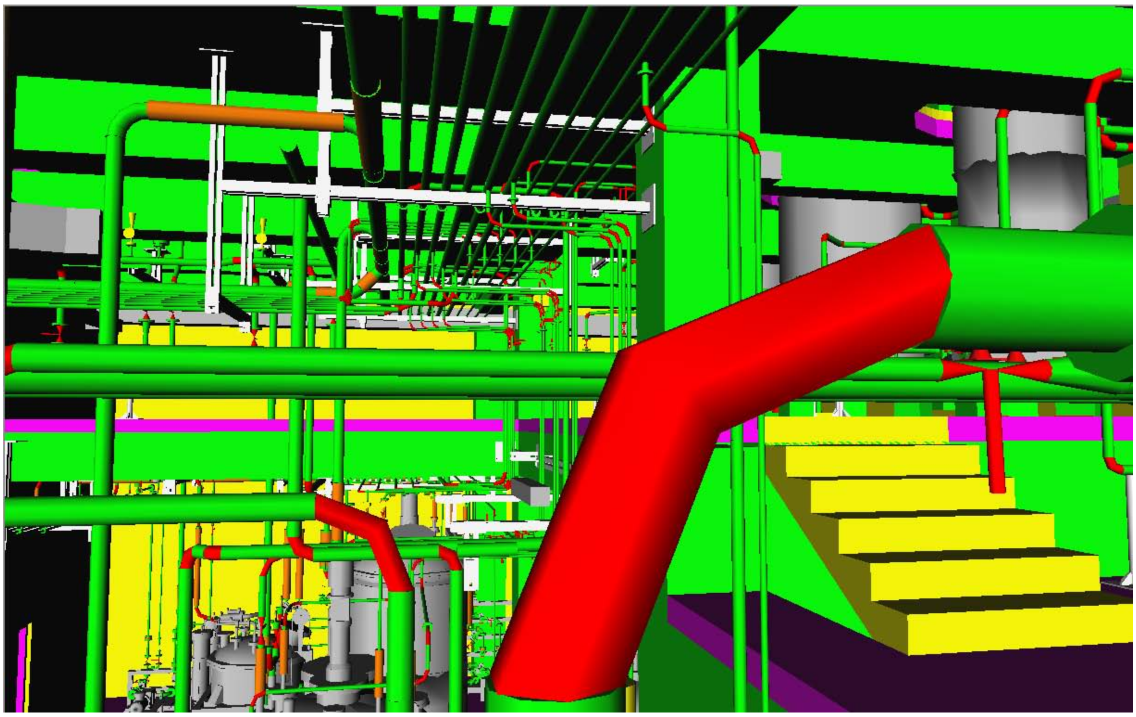


Figure 74. Detail on object-space semantic simplification. The elbow in this figure is recognized as an ISO-STEP elbow (COD. 4.2.66), and rendered in with geometric LOD technique for a piping engineer in a PC with limited resources

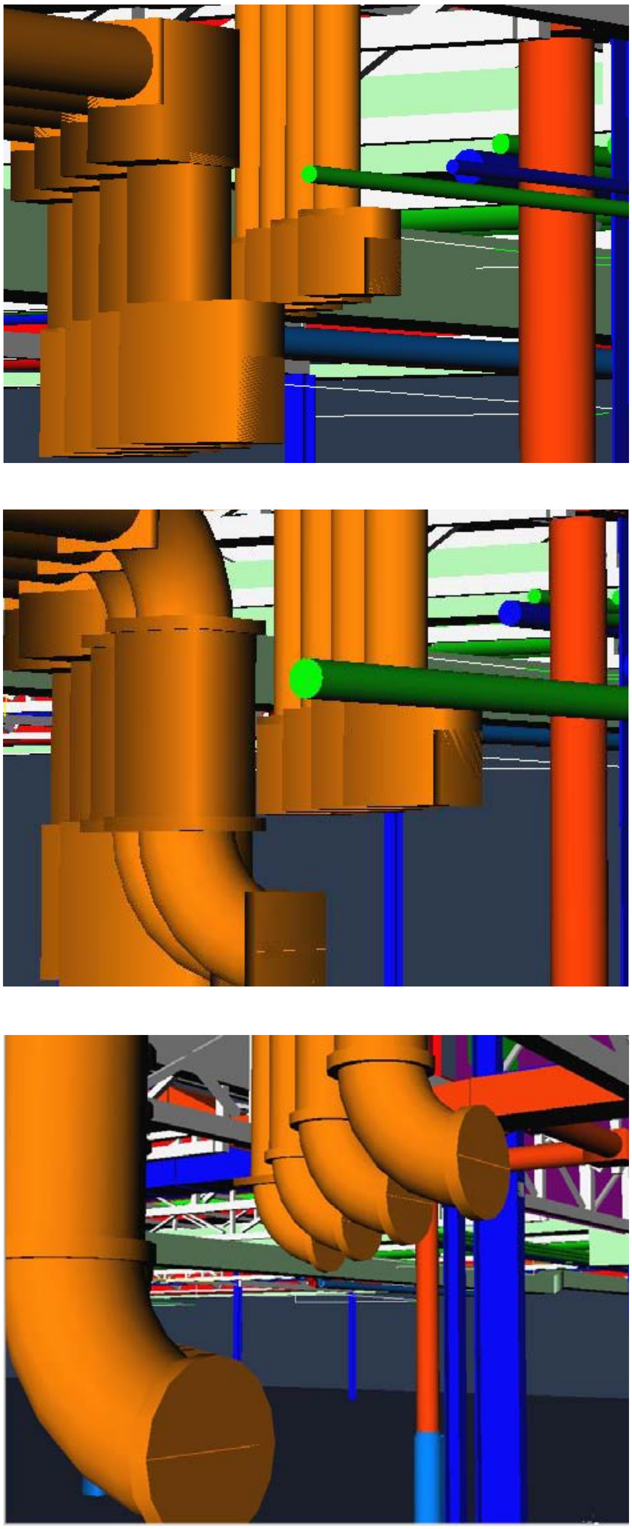


Figure 75. Another Example of technique steered by semantic considerations in the methodology. When suitable for a user / purpose / model / resources combination, simple LOD switches activate alternate representations of objects during walkthrough.

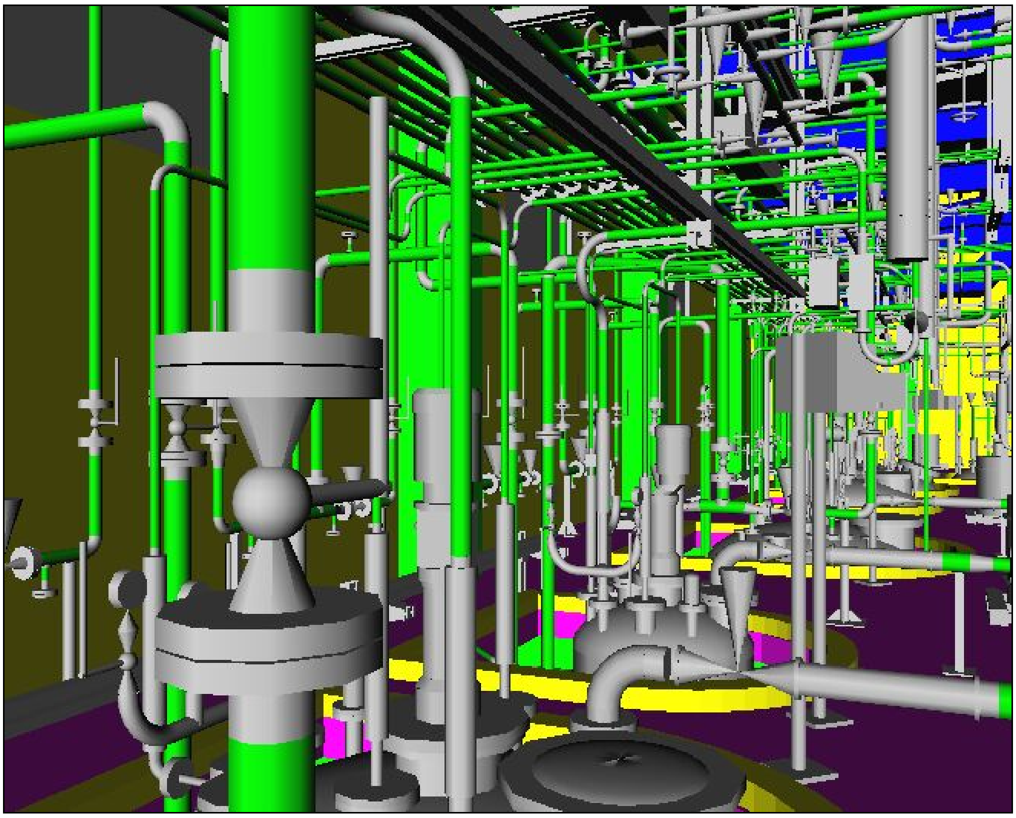


Figure 76. A complex view of the chemical plant's upper floor– detailed representation. User: piping engineer. Purpose: presentation to customer

Figure 77. Chemical plant upper floor, displayed for a manager. Purpose: work progress assessment. The valves (in red) are replaced with 3D semantic synonyms.

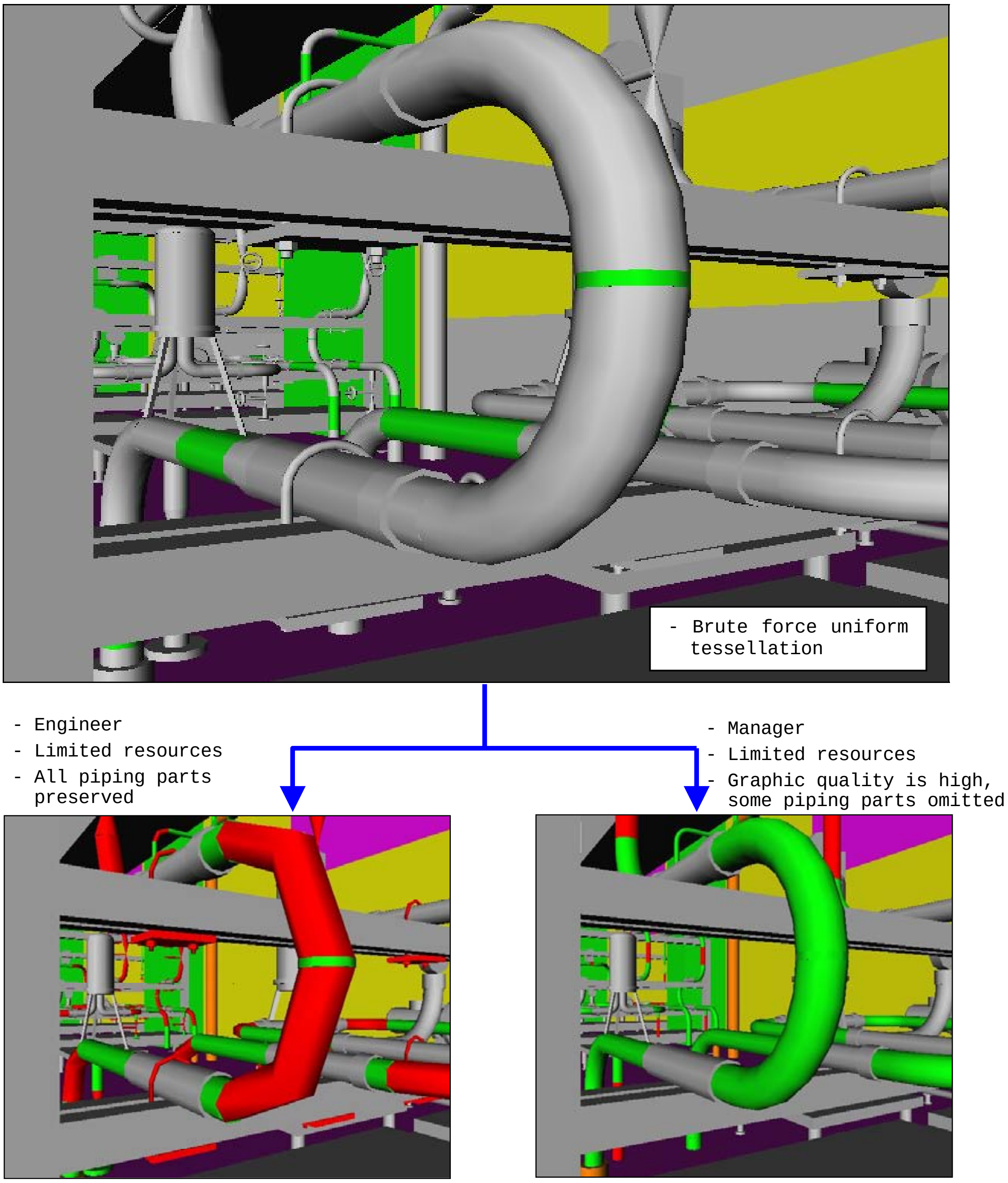


Figure 78. Example of semantic-steered techniques applied to the same model selectively, according to the domain, user and resources (semantic triangle). The brute-force tessellated model is shown above. Left: Adapted view for an engineer. Tessellation complexity of clamps and elbows reduced. Right: Adapted model for manager: high tessellation quality for elbows but no clamps

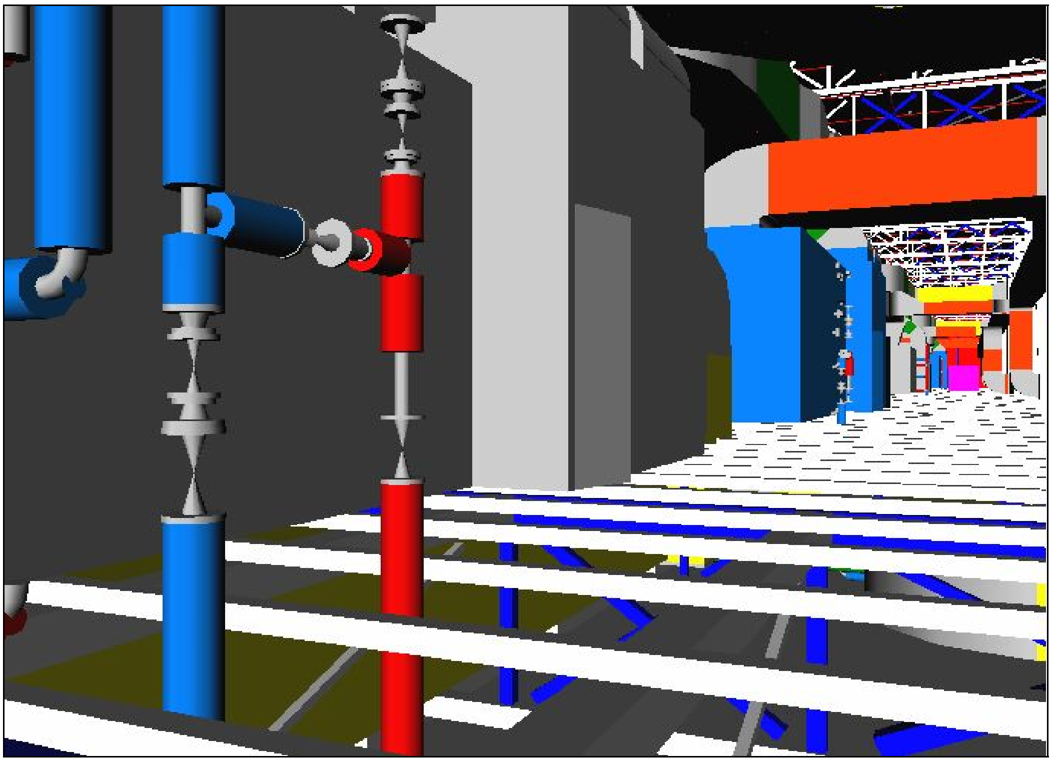


Figure 79. A view of the process plant model for an engineer. The valves are rendered as 3D symbols.

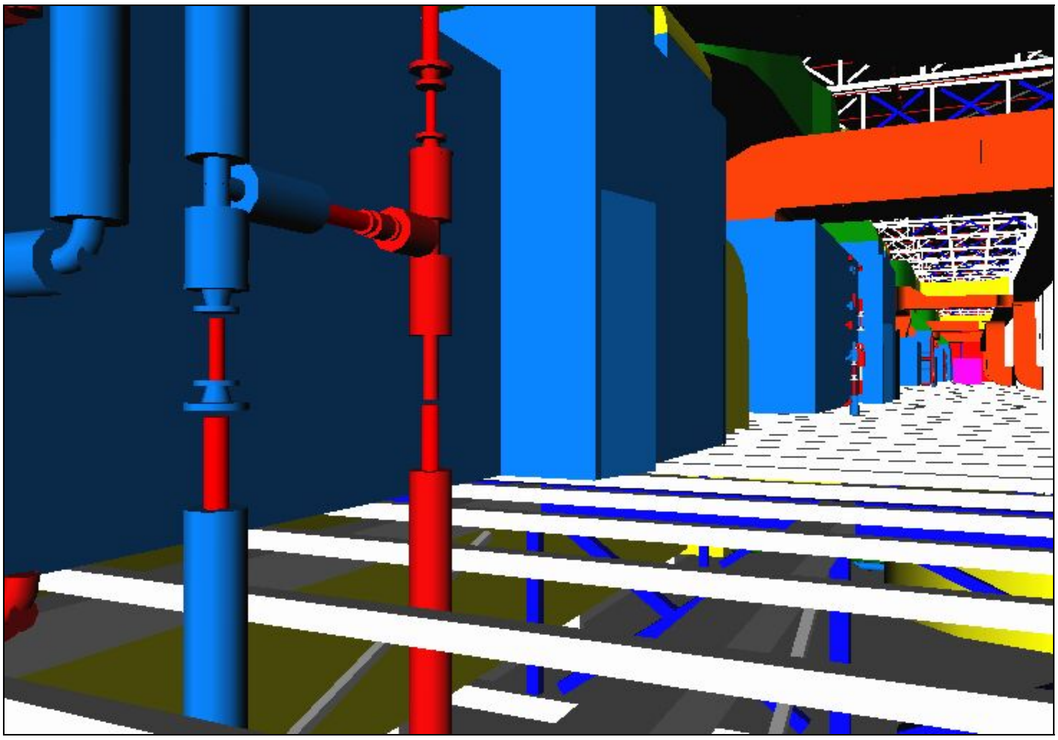


Figure 80. Process plant: Adapted view for a manager. Notice, in comparison with previous figure, that valves are *replaced* by straight pipe sections – a valid semantic simplification of the model for some user profiles/purposes.

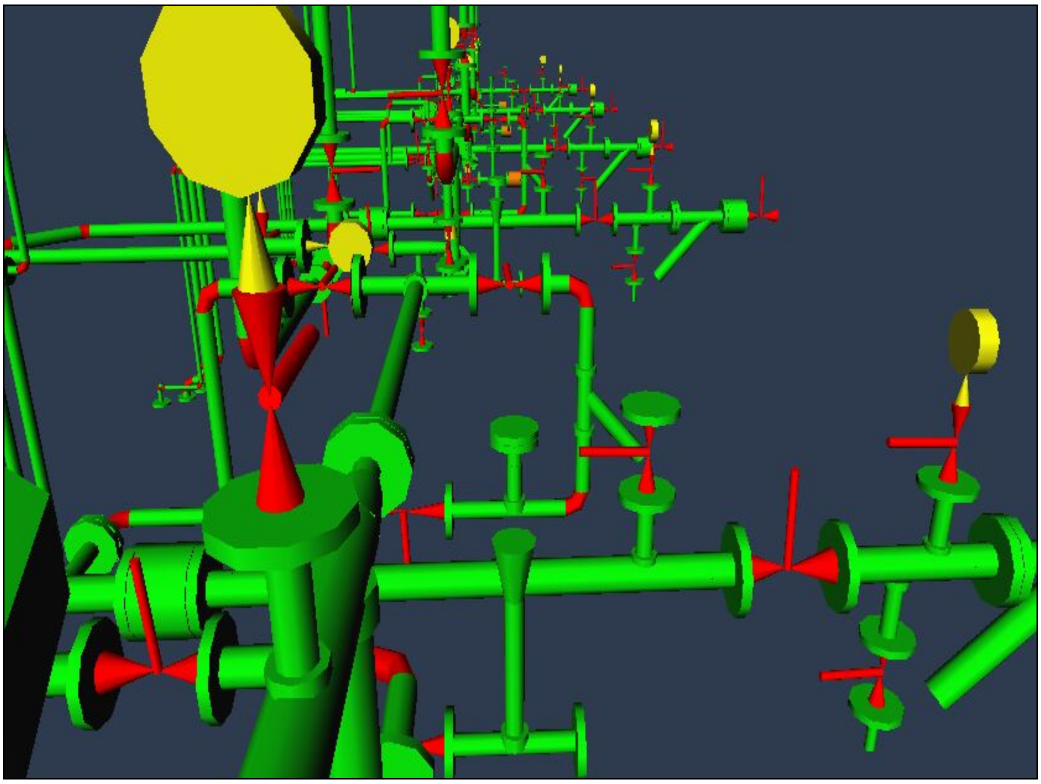


Figure 81. Chemical plant semantic simplification example. Case 1: User profile piping engineer, purpose: collaborative visualization. Valve representation, identified as ISO-STEP 10303-AP227 COD. 4.2.264, is done with 3D semantic Symbols.

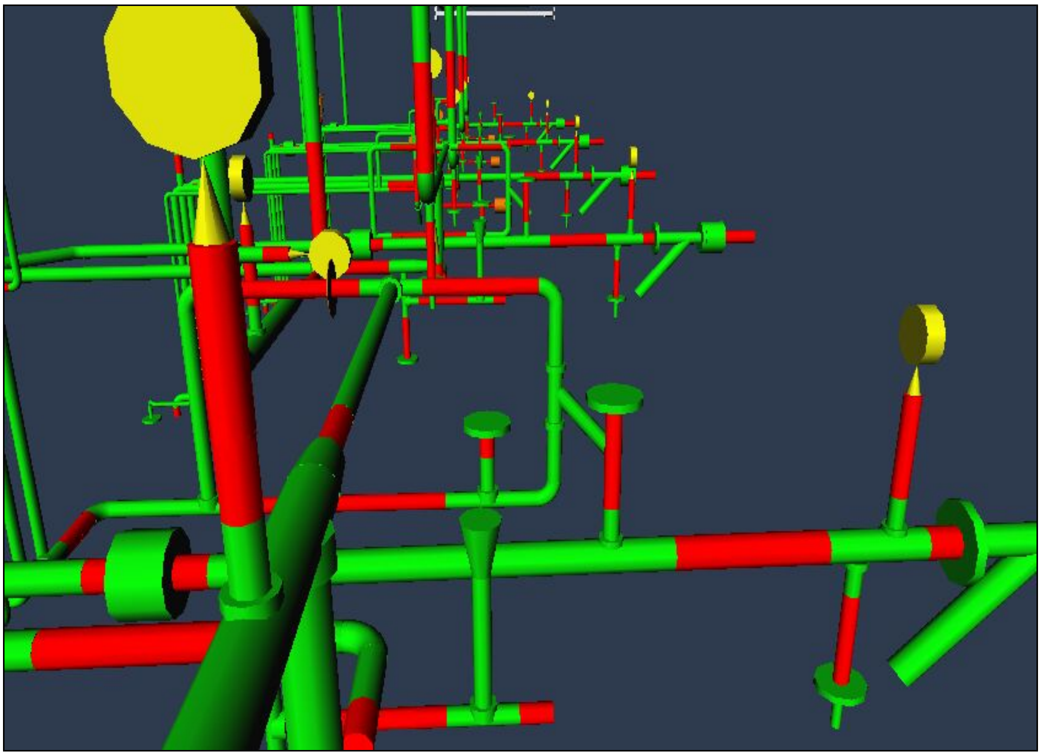


Figure 82. Chemical plant semantic simplification example. Case 2: User profile manager, purpose: work progress assessment. Valve representation, identified as ISO-STEP 10303-AP227 COD. 4.2.264, is done *replacing* valves by straight sections.

6.8 Evaluation of the Semantic Visualization Walkthrough Module

In this section I present the results of the evaluation of the *Semantic Visualization Walkthrough Module*, as well as the acceptance of the system by real users performing typical tasks of the Industrial Plant sector. I have followed the methodology of *standard evaluation procedure for 3D interaction – Step-3d* suggested by Grissom and Perlman in [GRIP95]. Thus, the reactions of the users could be better contrasted since a standard methodology has been used. Although the scope of the *Step-3d* is mainly focused on 3D interactions, without special considerations about the domain or semantic aspects, it gives a basic underlying framework to measure on the one side quantitative and in the other side qualitative results, related with the user feedback on the semantic visualization walkthrough system.

I have followed the rating schema of Grissom and Perlman, that goes from 0 to 7 being always 7 the most positive score and 0 the most negative score regarding a specific characteristic being evaluated. Some of the basic manipulation and interaction possibilities of the viewer are directly related to Step-3d whereas others are more generic.

The user tests were performed by six persons of different backgrounds and interests: Industrial Plant designers and engineers, computer scientists and "general public" –users without particular knowledge of the domain-. They were using the *MiroWalk* visualization module with different 3D adapted models from the Plant Design domain.

Figure 83. Industrial Plant Designer and Piping/structural Engineer during the evaluation

I have evaluated the following aspects, using six users and two different 3D CAD models of Industrial plants:

- Ease and intuitiveness of interaction
- Design review purpose: Error search (visual collision detection)
- Effectiveness in motion to specific parts in the model
- Search for an object
- Comparison between normal representation and *symbolic synonyms*
- Trade-off between accuracy in geometry representation vs. speed and interactivity of walkthrough experience

Next I will present the two different tests that were used for the evaluation, as well as a summary and analysis of the results.

Figure 84. Some screenshots of users with specific purposes in *the Semantic Visualization Walkthrough viewer*

6.8.1 Evaluation of interaction and task performance

I will discuss here the most important results obtained for an adapted 3D CAD model of a process plant. The questionnaire used can be seen in Annex I. The six users were asked to use the viewer for 10 minutes in order to evaluate several issues concerning interaction and purpose performance. The grading was from 0 to 7 as explained in the introduction of this section.

6.8.1.1 General options of the viewer –3D Interactive Visualization aspects

The following table shows the results for the features available in the visualization tool (question 1 of the questionnaire). They are grouped into different categories:

- General motion through the plant using the mouse (3D Space Mouse is also supported)
- Interactive camera aspects (such as zoom, perspective, etc.)
- Selection and Manipulation possibilities
- Some functional options (hierarchical tree view, measuring tools, part data options)

Results

The results are shown in the Table 21 below.

Analysis of the results

The average values given by different users were quite similar on the provided functionality for interaction and visualization. As it can be seen in the Table 21 most features are evaluated with a high score (overall average **5,62 / 7,00**) in the general task of walking through the model. In general, the movement through the model and the interaction possibilities were evaluated with a very positive score.

It is interesting to notice that some specialized visualization modes (such as key points visualization) have given low values. This reflects that the *general user* has little knowledge of the elements, as they appear to him as a soup of points without connection information. However, for specific *user profiles / purposes*, this proved to be helpful: a designer wanted to identify the density of bolts in a specific region, and could successfully do so, since the density of the elements represented more points in the visualization.

Table 21. Results of the evaluation on Visualization and Interaction on 3D CAD Industrial Plant Models with *Mirowalk Viewer*

Feature	Average Score
Mouse movement, forward and backwards	6
Mouse movement, up and down	6
Mouse movement, rotation	6
Alternative mode (Examiner mode)	5
Right button (Wire frame mode)	6
Right button (Points mode)	4
Button (Full Screen)	6
Movement wheels	6
Zoom factor (Camera)	6
Save/Recover, camera position	6
Model's global perspective (fit)	6
Get close to an element (Seek)	6
Hierarchical view (Tree view)	5
Graphical environment selection	6
Selection and hierarchical view coordination.	6
Translation manipulator (Transform box)	5
Rotation manipulator (Center ball)	5
Element data (Part data)	6
Standard file options	5
Measuring tool (Measure)	5
Parts family catalog	6

Another interesting result was the relatively low score of the *tree view* functionality, in which the user can see the hierarchical distribution of the model structure. Although a score of **5** is not bad at all, I interpret that either the purpose was not properly defined in this case, or a it a better metaphor for visualization, searching and manipulation on the hierarchical structure should be developed.

6.8.1.2 Specific task for user profile Designer / Engineer

The Designer/Engineer users were asked to perform an action typically performed in a Design Review visualization purpose: to find an *collision between two components (a piping component and a structural part)*. The specific collision was previously selected in the model and shown to them as a screenshot, in which it was possible to understand the nature but not the specific location of the problem.

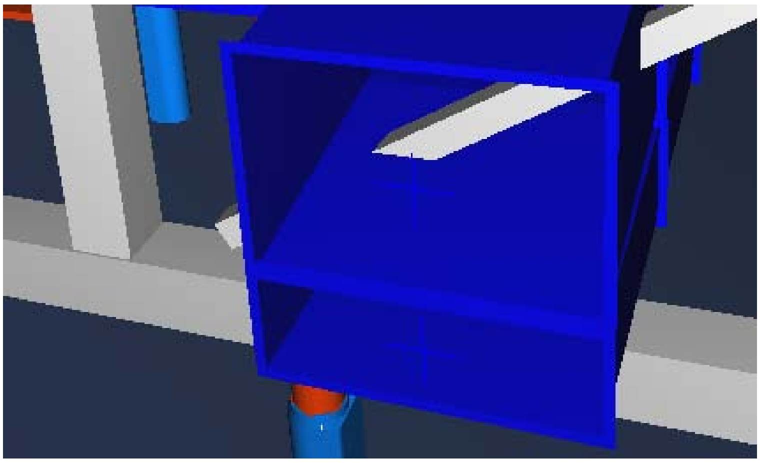


Figure 85. Design Review Purpose: Users where requested to find a collision between two components

Results

The users were asked (point 2 of the test) about the subjective score regarding the *ease* of finding such a problem. The average score was almost **6,** indicating that persons with a suitable background scored this possibility high. The non-expert users gave a lower score (below **5**), for an overall average of **5.**

The time to find the error was also computed, in average it was **81 seconds.**

Analysis of the Results

The users could find in all cases the required error during the Design Review purpose. There were some differences in the time needed by expert users in the domain in comparison with other users. As an interesting side-effect of the test, one of the users found several different occurrences of the error shown. The time needed to find the problem is considered to be quite efficient in comparison with inspection in the native CAD system.

6.8.1.3 Ease of movement through the model – visit key places

All users were requested to perform a simple purpose: to visit 4 key locations in the model. These key locations are reference to look for in a typical purpose.

Results

The average result was **5**, which is good considering that the users were not familiar at all with the system before using it during the test. The users also took an average of **73 seconds** in going through the model as requested.

Analysis of the results

Naturally, the fluid, immersive movement through the adapted model is a key factor for the success of *almost any purpose* related with walkthroughs in an Industrial Plant model. A score of **5** or more is considered as very good, since the users were not familiar with the system before using it. For a large CAD model of this process plant, the time of **73 seconds** show on the one side some inexperience, but on the other a consistent learning curve for final results aligned between different users. I hypothesize that the use of different resources (e.g. Space Mouse) would not give a higher score, but would probably change the average time.

6.8.1.4 Finding instances of specific components of the Plant

Designers and Engineers, but also non experts, I requested to find a instances of a specific component of the plant. The selected element belongs clearly to the standard kind of components of Industrial Plant design; concretely, I have shown the picture of the 3D representation of a valve between 2 pipes. The users had to identify instances of the valve, and the time required was measured in order to compare the results between the different users.

Results

The users took an average of **66 seconds** to find instances of the standard model part. They correctly identified the kind of element that the 3D representation depicted. The ease of finding such an instance was scored with a **5.**

Analysis of the Results

The Designers and Engineers performed quite well in this purpose, since their conceptual understanding of the elements involved in Industrial Plant Design help them in finding the elements not only based on their geometrical representations, but also on the logical arrangement of such elements (valves) in the model. Other users had also interesting results.

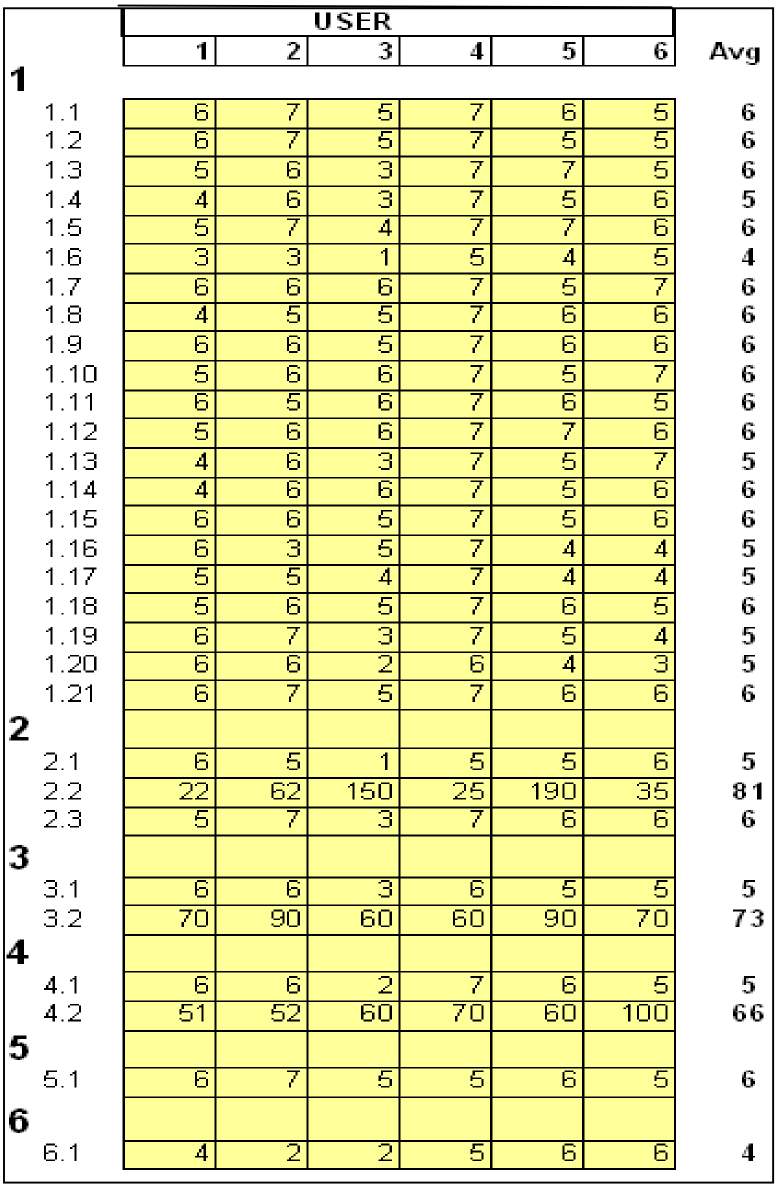
6.8.1.5 User interface – influence of WIMP paradigm in specific OS

The users were requested generic questions regarding the ease of use of the system combining a section of purely 3D–based interaction with a conventional model of Windows, Icons, Menus, Pointer (WIMP) using Windows Microsoft Foundation Classes as Operating system. Since these questions are not central to our research focus, the only comment we may give to this respect is that users did find interesting the possibility to complement interaction on the model with conventional menu-based interaction.

6.8.2 Summary of the results for Visualization & Interaction

The particular scores obtained in each test are shown in Table 22.

Table 22. Scores of all users for the Interaction & Visualization evaluation (see Annex II for more details on the specific questions)



		USER						
		1	2	3	4	5	6	Avg
1								
	1.1	6	7	5	7	6	5	6
	1.2	6	7	5	7	5	5	6
	1.3	5	6	3	7	7	5	6
	1.4	4	6	3	7	5	6	5
	1.5	5	7	4	7	7	6	6
	1.6	3	3	1	5	4	5	4
	1.7	6	6	6	7	5	7	6
	1.8	4	5	5	7	6	6	6
	1.9	6	6	5	7	6	6	6
	1.10	5	6	6	7	5	7	6
	1.11	6	5	6	7	6	5	6
	1.12	5	6	6	7	7	6	6
	1.13	4	6	3	7	5	7	5
	1.14	4	6	6	7	5	6	6
	1.15	6	6	5	7	5	6	6
	1.16	6	3	5	7	4	4	5
	1.17	5	5	4	7	4	4	5
	1.18	5	6	5	7	6	5	6
	1.19	6	7	3	7	5	4	5
	1.20	6	6	2	6	4	3	5
	1.21	6	7	5	7	6	6	6
2								
	2.1	6	5	1	5	5	6	5
	2.2	22	62	150	25	190	35	81
	2.3	5	7	3	7	6	6	6
3								
	3.1	6	6	3	6	5	5	5
	3.2	70	90	60	60	90	70	73
4								
	4.1	6	6	2	7	6	5	5
	4.2	51	52	60	70	60	100	66
5								
	5.1	6	7	5	5	6	5	6
6								
	6.1	4	2	2	5	6	6	4

6.8.3 Evaluation of Influence of Semantic symbols and Semantic Factors

In this section I discuss some of the results of the user evaluation regarding the introduction of semantic symbols and semantic factors as a support for the adapted representation of the plant. The main objective of this part of the test was to evaluate the balance between geometric accuracy, functional expressivity and resource management introduced by the semantic symbols technique, as well as to adapt better the values for the aesthetic factor *fges* and the semantic factor. The model used was a complex, real-life model of a chemical plant in 3D. The questionnaire used can be seen in Annex II. The six users were asked to perform some tasks regarding:

- The immersion and interactivity perception
- The subjective evaluation of functional and aesthetic factors

The grading was from 0 to 7 as explained in the introduction of this section.

6.8.3.1 Brute force tessellation representation on limited resources

In this test the users were asked to navigate through a model that was tessellated with the brute force technique in a computer with limited resources. The elements were depicted with high geometric accuracy, but with the drawback that the interactivity was seriously impaired. Figure 86 shows a screenshot of that model. Notice the very detailed representation of the clamps, elbows, tanks, etc. in the model.

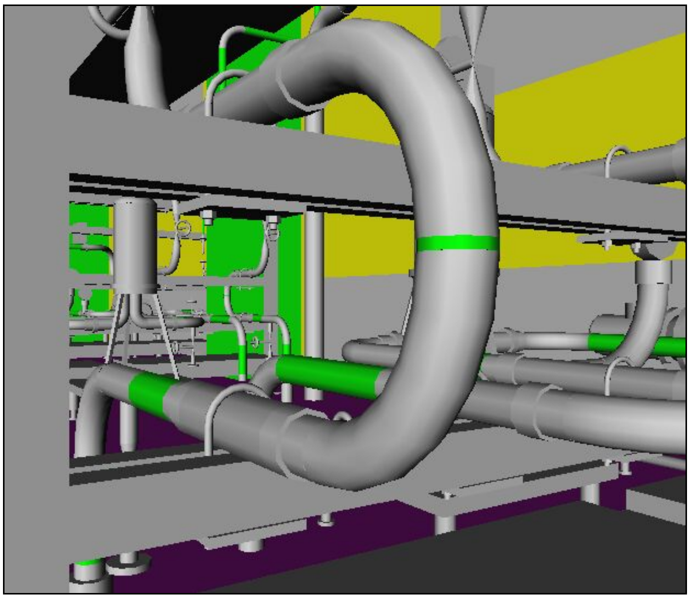


Figure 86. Brute force tessellated model – Screenshot. All details are included at high rendering cost

Results

The average value for the ease of movement and immersion perceived was only scored with **3.** On the other side the subjective quality associated to the different elements in the model (components of the plant) was scored very high, with **6.** The model given was about 25% of the model size of the next part of the test.

Analysis of the Results

The values correspond with the expected situation: high accuracy representation (with unconstrained number of triangles per component) is well rated by all users, of all backgrounds. However, if this affects the performance of the walkthrough due to resource constraints, the overall experience is rated very low.

6.8.3.2 Adapted model with semantic symbols

In this test the users were asked to navigate through a model that was tessellated with the *semantic symbol* technique for only 3 elements: *valves*, *elbows* and *flanges.* This allowed the representation, on the same resources, of a model that was 4 times larger than the previous one, with higher *fps* rates. Figure 87 shows a screenshot of that model.

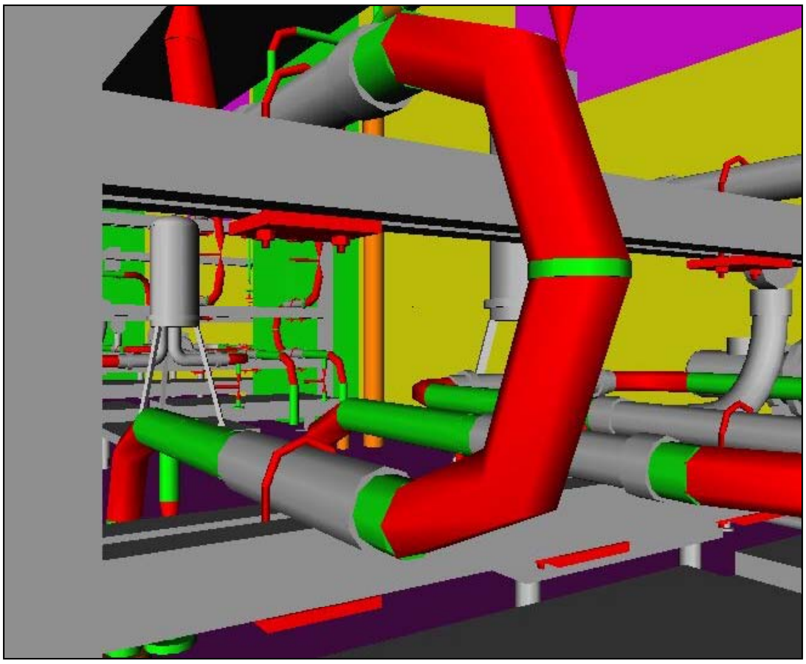


Figure 87. Model of the plant with adapted representation using semantic symbols – simplified model.

Results

The users, from different backgrounds, gave an average of **5** to the ease of movement and interactivity on the model. The subjective quality assigned to the task objective (Design Review) on the model was scored in average with **6.**

Analysis of the Results

It is very interesting to notice that in general there was no important difference between the subjective perceived quality in both cases, although for some specific user profiles (especially engineers) the change was evident –in all cases one point less: two of them from 7 to 6, and one from 6 to 5. The most important change came from the evaluation of the walkthrough interactivity, which increased from **3** to **5.** Thus, I conclude that semantic symbols indeed improved the overall perception of the experience, for both engineers and non-technical persons.

6.8.3.3 Some feedback regarding semantic symbols

In this final part of the test the users gave some feedback regarding the following aspects, on the model adapted with semantic symbols:

- Identification of engineering parts
- Identification of perceived changes on the model
- Evaluation of semantic and aesthetic factors

Results

Most users could successfully identify at least 5 different engineering elements in the model that were represented with semantic symbols instead of detailed –or simplified-geometric representations.

All users noticed the difference between the initial model and the adapted model in terms of interactivity and visual representation. However, they considered the changes as positive from a semantic/functional perspective (score **6**), even those changes related with less detailed representations.

However, all users agreed on giving a lower score to the geometric-aesthetic factor, which was also expected in our framework.

Analysis of the Results

In Table 23 the summary of the *fges* evaluation is given. Clearly, the users have preferred the detailed representation (this was an expected result) and have scored consistently lower values in this aspect for the semantic symbols.

Table 23. *fges* – Geometric – Aesthetic Factor evaluated by users

Elements model	Valve	Elbow	Flange
Without semantic symbols	5	5	5
With semantic symbols	4	5	3

However, the *semantic functional factor – fsem* was evaluated positively by all users, indicating that the loss of subjective quality in the graphical representation did not influence the comprehension and understanding of the model. The summary of the values given is in Table 24.

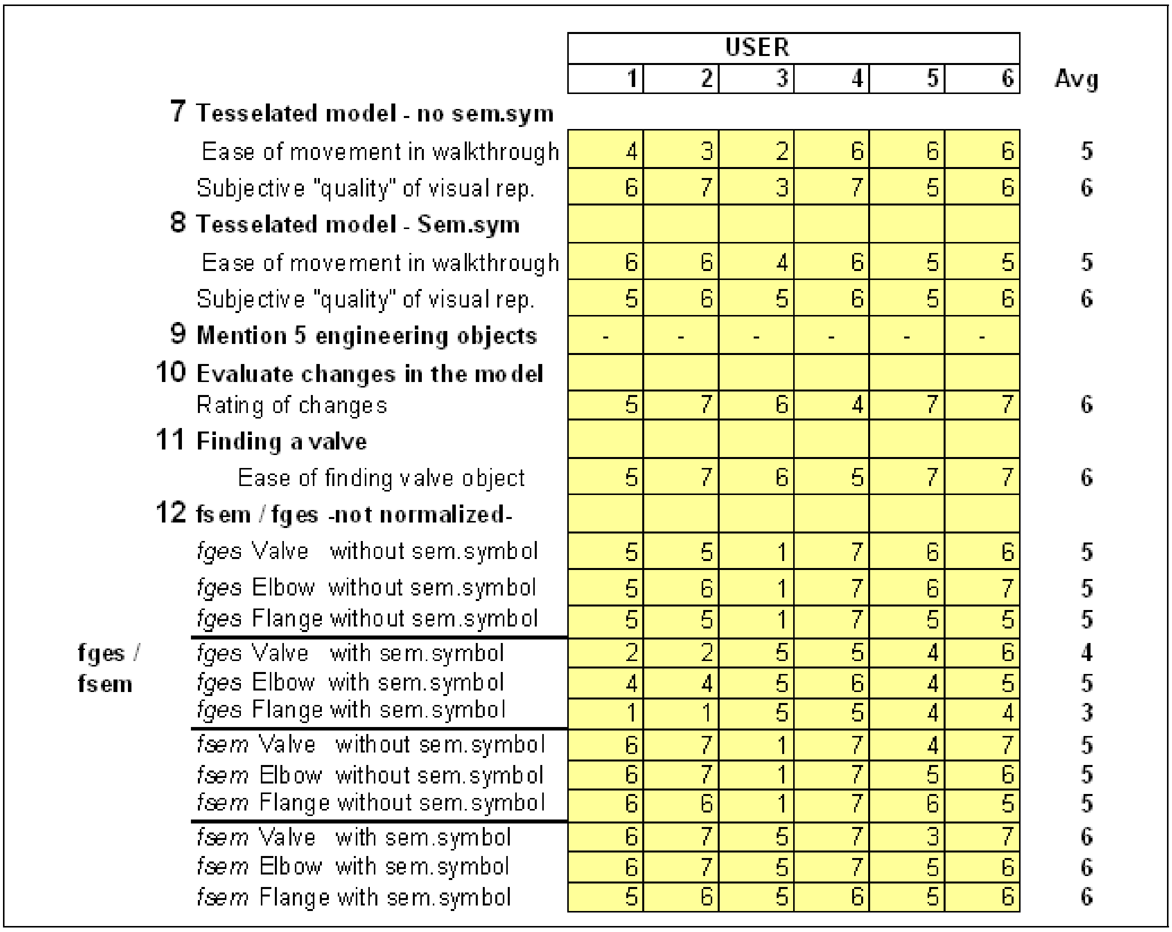
Table 24. *fsem* – Functional-Semantic factor evaluated by users

Elements model	Valve	Elbow	Flange
Without semantic symbols	5	5	5
With semantic symbols	6	6	6

In general, it was confirmed that for the purpose of the *design review purpose*, by different users, the change introduced by the semantic symbols improved the visualization for the goals and background of the users, even considering the subjective perception of some loss of quality in the geometric representation, but not in the functional/semantic aspects.

The next table shows a summary of the questionniare section related with the semantic symbol technique.

Table 25. Summary of questionnaire section for influence of Semantic Symbols and Factors



			USER						
			1	2	3	4	5	6	Avg
	7	**Tesselated model - no sem.sym**							
		Ease of movement in walkthrough	4	3	2	6	6	6	5
		Subjective "quality" of visual rep.	6	7	3	7	5	6	6
	8	**Tesselated model - Sem.sym**							
		Ease of movement in walkthrough	6	6	4	6	5	5	5
		Subjective "quality" of visual rep.	5	6	5	6	5	6	6
	9	**Mention 5 engineering objects**	-	-	-	-	-	-	
	10	**Evaluate changes in the model**							
		Rating of changes	5	7	6	4	7	7	6
	11	**Finding a valve**							
		Ease of finding valve object	5	7	6	5	7	7	6
	12	**fsem / fges -not normalized-**							
		fges Valve without sem.symbol	5	5	1	7	6	6	5
		fges Elbow without sem.symbol	5	6	1	7	6	7	5
		fges Flange without sem.symbol	5	5	1	7	5	5	5
fges / fsem		*fges* Valve with sem.symbol	2	2	5	5	4	6	4
		fges Elbow with sem.symbol	4	4	5	6	4	5	5
		fges Flange with sem.symbol	1	1	5	5	4	4	3
		fsem Valve without sem.symbol	6	7	1	7	4	7	5
		fsem Elbow without sem.symbol	6	7	1	7	5	6	5
		fsem Flange without sem.symbol	6	6	1	7	6	5	5
		fsem Valve with sem.symbol	6	7	5	7	3	7	6
		fsem Elbow with sem.symbol	6	7	5	7	5	6	6
		fsem Flange with sem.symbol	5	6	5	6	5	6	6

7 CONCLUSIONS AND FUTURE WORK

7.1 Conclusions and main contributions

The main contribution of the present work is the conception, implementation and evaluation of a methodology for the ontology supported semantic visualization of 3D CAD models of Industrial Plants for Virtual Reality walkthroughs. This methodology takes into consideration the user profile and intention, the purpose context and the optimization of available resources, as well as international standards for the data representation and exchange in the domain of Plant Design (ISO-STEP 10303-AP227).

This work combines Computer Aided Design, Computer Graphics and Semantic Technologies to provide a sound basis for the introduction of semantic aspects in the area of Large Model Visualization, which has been associated in the past mainly with optimization of resources and improved visualization algorithms, with little consideration on the specific domain and the user background and interest. Even existing commercial systems in the area do not address these aspects well, focusing mainly in *fps* performance and relation with other PDM information when available. In the proposed methodology, the traditional approach is enhanced by explicitly introducing semantics in different steps of the process of generating interactive visualization walkthroughs of 3D Industrial Plant models.

A novel modular architecture has been proposed which allows the implementation of the different conceptual steps in the methodology as connected modules. Each module helps to have a more explicit representation of the semantics inherent to the model, but also to the user and the domain. Thus, the methodology starts from a complex 3D CAD geometric model of an industrial plant, and adapts it incrementally to a suitable model for a specially generated visualization walkthrough experience for a specific user and purpose.

The objective of a Virtual Reality interactive walkthrough of an Industrial Plant model is different for each user and purpose. Certainly it is not a general purpose interactive visualization of the 3D model of the plant. An engineer may want to perform Design Review on specific components and layers of the plant. A Manager may want to become a general impression of the ongoing modelling progress. Also, the resources available are not always the same: they can vary from normal PCs in the workplace to special showrooms with large screen projection. All these important aspects can be now considered in the methodology.

Emerging tools for ontologies management have been used extensively in this work, as natural support for most of the semantic related aspects in the system. This approach has given an innovative way to use these semantic technologies, well suited for the representation of concepts and relationships in a domain, in a new application field. In fact, several recent developments in research of computer graphics for industrial applications (as for instance the European Projects AIM@Shape, SmartSketches and SpaceMantix) point to the same direction of this work, albeit in different stages:

> *The next generation of Computer Graphics technologies for the Product Development Cycle will include an increasing semantic dimension in the model and the processes.* (see Figure 9).

This contribution is crystallized in the present work in an innovative approach: the ontology support for (i) adaptation to the ISO-STEP 10303 Standard, (ii) User/Purpose support and (iii) Techniques selection for tessellation, with the clear objective of generating adapted representation of the Industrial Plant model for a specific user and purpose.

A key point in the methodology is that the adaptation follows a conservative policy for the use of available resources, and makes a more rational selection of tessellation techniques, fulfilling the semantic and domain constraints required for the visualization purposes, in contrast to rely only in the increasing power of graphics hardware.

A simple but effective mathematical model was developed for the conceptualization of all the modules of the methodology. Consequently, the semantic adaptation and visualization problem can be treated as a mathematical problem. For the initial modules (*Catalog Reconstruction and ISO-STEP 10303 Adaptation*) a mapping of the problem is done from the point of view of the mathematical Set Theory. For the *Semantic Adaptation Module* and the *Adaptive Representation Module* a customized, simple formulation of the problem is given from the Optimization Theory perspective. As a result, an optimal selection of object-based tessellation techniques can be chosen for families of components, according to constraints given by the user/purpose context.

A complete system based on the proposed methodology and architecture has been implemented, and tested with several real world models of Industrial Plants. This has led to some innovative aspects in each module. New techniques in the *Catalog Reconstruction Module* allow for a reconstruction of the inherent instance and component-based structure of the model, beyond the mere geometric description of individual CAD primitives. In the *ISO-STEP 10303 Adaptation* a semiautomatic process for relating families of parts to the standard has been implemented, with innovative use of ontology querying & visualization mechanisms. The *Semantic Adaptation Module* relates explicitly separate ontologies (user, purpose, resources and techniques), modelled and queried with ontology tools from the research community, to find based on an optimization problem the most suitable combination of tessellation techniques to apply to the adapted model. Finally, the *Adaptive Representation Module* and the *Semantic Visualization Walkthrough Module* apply those techniques and present the resulting model to the user in an integrated walkthrough experience adapted to the available resources, with several purpose-related functionalities beyond the mere navigation through the scene.

The extensibility and generality of the methodology is twofold: On the one side, the approach it is extensible to other *application domains* requiring the generation of specially adapted visualization and walkthrough experiences from 3D CAD models (as in the case of car design, which also has a STEP standard, see [GBS02].). On the other side, for the domain of Industrial Plant Design the methodology is extensible to other *techniques, resources, user types and purposes,* which can be added straightforwardly. Thus, the system can incrementally increase its performance and user/purpose adaptability.

The fact that the methodology is based on a standard for the domain –even when that STEP standard was defined for exchange of product data- also accounts for the generality of the approach.

The developed system has been used in several research projects in the Industrial Plant visualization area, mainly in Fraunhofer Institute for Computer Graphics and the INI-GraphicsNet institutes, in cooperation with companies active in this sector. It is being used currently in two industrial research projects with international participants. The results presented show that the quantitative and qualitative aspects of the walkthrough experiences on the adapted model improved both the performance and the effectiveness with respect to other approaches.

Finally, some conclusions with regard to the relation of this work with other related approaches. Outstanding performance results are being obtained by several research groups on Large Model Visualization of engineering models, including industrial plants (see especially [BSG02]), as well as other kinds of models (aircrafts, submarines, cars, etc., see [CORR04]). The proposed methodology of this work seamlessly complements these efforts, since the techniques and algorithms developed in those groups can be integrated in the methodology (mainly in the *Semantic Adaptation* and *Adapted Representation* modules) without loss of generality. The same can be said with regard with commercial products from specialized companies; clearly, the objective of this work is not to compete against or improve solely the pure performance of walkthroughs of large models, but to introduce a general methodology that takes into consideration semantic aspects from the domain, user, purpose and resources to provide more effective visualization walkthroughs for Industrial Plants.

7.2 Future Work

The proposed methodology has been implemented and tested with several models and use scenarios. Nonetheless, there are still several open lines for extension and improvement. An important open issue is to work in more depth in the treatment of semantic aspects of CAD components in the specific domain of Plant Design, not only for visualization-related purposes, but also for other purposes related to functional modelling of the processes of the plant. The fact that a STEP standard exists in this domain is helps but does not solve all related issues, since many legacy systems do not support such standard, and since it is mainly a data-oriented representation model for exchange of product data (not a fully functional/semantic representation for specific users and purposes). In this sense, an investigation on the work of Mizoguchi Lab at Osaka University (see [MKS00]) and its possible synergies with the presented work, is a promising possibility. Initial contacts have been recently started with that group.

On the algorithmic side, improvement potential is envisaged on the automatic recognition (semantic enhancement) of the 3D CAD representation of Plant Design components, when this information is not available from a PIM system –which is a mainstream situation-, beyond feature recognition algorithms and other similar approaches. The presented techniques showed a good progress in this regard (as presented in the results section), but still many 3D CAD objects from different software producers are still not correctly identified and classified according to the standard.

An extension of the mathematical model as well as the *Adaptive Representation Module* to include also spatial-based techniques such as advanced culling should be very beneficial for improvement of performance issues. The same can be said about new object-based techniques not included in the current implementation. Future support to more resources (e.g. PDA mobile walkthroughs in the Plant) and networking technologies (including streaming solutions for mobile or concurrent engineering scenarios) is also envisaged.

Further study on the use of ontologies and other semantic technologies for this domain is clearly an area with potential for future work. The tools and specifications used by initially by the AI community (and now more and more by the engineering community) for management and querying ontologies –I have used Protégé and OWL- are still research efforts with interesting aspects to explore in the potential synergies with Computer Graphics and Computer Aided Design communities.

Another interesting future work line, as extension of the methodology, is the integration of *semantic interaction of virtual characters* inside the virtual model for Design Review purposes of the Industrial Plant. The inclusion of virtual characters for assisting maintenance purposes in virtual models is an existing research area, as it can be seen for example in the work of ZGDV-Rostock (see Figure 88)

Figure 88. Future semantic interaction of avatars in Industrial Plants – (with permission from Zentrum für Graphische Datenverarbeitung, Rostock)

This is a research line I have already started to explore, as sketched in one of the last publications of our group related to this work (see [OOTP05] and [CARR05]). I will apply techniques related with body animation (inverse kinematics calculations, predefined animations, collision detection, etc.) and to semantic modelling of design review issues, to extend our methodology, in order to (i) obtain adapted, purpose-oriented movement around the plant, (ii) to verify accessibility issues for set-up, maintenance and daily operation of the plant components.

Another direction of future work is the support of the Mirowalk system to different hardware/software VR setups beyond workplace PC and simple projection setups (Figure 89)

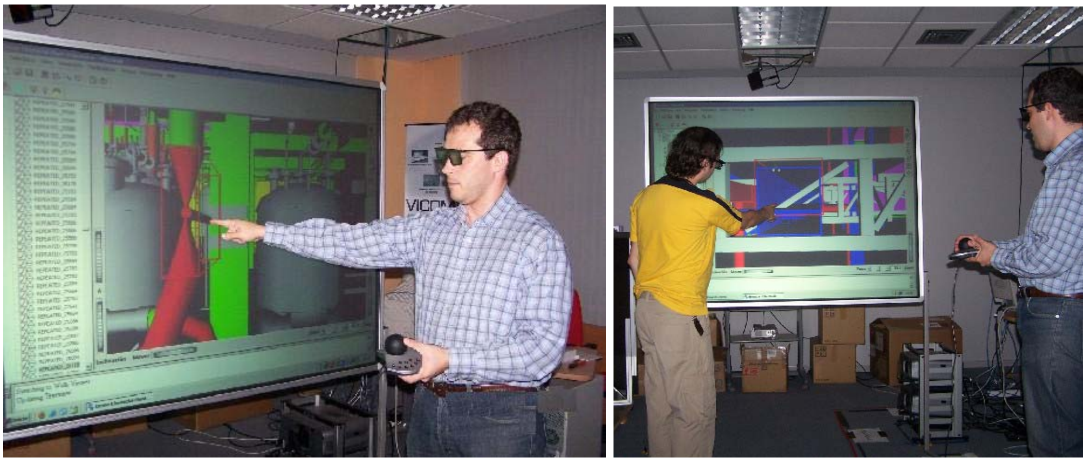


Figure 89. The *Mirowalk* system in a simple VR setup with passive stereo and back-screen projection, using a SpaceMouse as input device.

8 BIBLIOGRAPHY AND RELATED PUBLICATIONS

In the first part of this chapter, I present some of the publications related with this research. In the second part, I present the general bibliography referenced in this work.

8.1 Publications related with this research

8.1.1 Journals and Book Chapters

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LIST OF FIGURES

LIST OF TABLES