A Methodology for the Semantic Visualization of Industrial Plant CAD Models for Virtual Reality Walkthroughs

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Erklärung: Hiermit erkläre ich, daß ich die vorliegende Arbeit selbstständig und unter ausschlielicher Verwendung der angegebenen Quellen und Hilfsmittel angefertigt habe.

Darmstadt, den Oktober 25, 2005

ZUSAMMENFASSUNG

Es gibt immer noch viele offene Themen und Fragen in bedeutenden Bereichen der Visualisierung grossen Modelle im Fabrikplanungsbereich (*Large Model Visualization* – LMV- *for Plant Design*). Leistungsfähigkeit, um interaktive Raten für sehr grosse Modelle zu erreichen, ist bestimmt eine von diesen, besonders wenn die Ressourcen beschränkt sind, jedoch ist es nicht mehr der kritischste Punkt. Verschieden Techniken und Algorithmen, die heute verfügbar sind betrachten nur ganz wenige –oder gar keine- semantische Aspekte. In der Forschungliteratur sind hauptsächlich Algorithmen und Methoden für Geometrie und Szenegraph-Rendering zu finden. Solche Ansätze nehmen an, dass Darstellungsprobleme in der Visualisierung für Fabrikplanung aus den rein geometrischen Dimension der CAD-Modelle resultieren, wobei die Realität zeigt, dass in diesem bestimmten Bereich auch Domäne, Benutzerprofil und Absicht eine ebenso wichtige Rolle spielen. Diesbezüglich werden folgende Aspekte nicht genügend beachtet: (i) Die Modelle gehören zu einer besonderen, gut begrenzten Domäne im Ingenieurwesen (Fabrikplanung - *Plant Design*), in der Semantische Aspekte formalisiert sind (mittels bestimmten Standards, z.B. ISO-STEP 10303- AP227); (ii) die Benutzer haben verschiedenen Profile und Absichten in der Visualisierung; und (iii) die Visualisierung des Modelles für eine *Walkthrough*-Navigation kann spezifisch für jeden Benutzer im Kontext seiner bestimmten Absicht adaptiert werden, um eine optimale Distribution von Techniken und Ressourcen zu schaffen.

Die Hauptmotivation und der Untersuchungsfokus der vorliegenden Arbeit, unter Berücksichtigung der oben aufgeführten Aspekte, ist *die explizite Einführung semantischer Aspekte in der Visualisierung grossen Modelle im Fabrikplanungsbereich, um besser geeignete Visualisierungerfahrungen für bestimmten Benutzern, Absichten und verfügbare Ressourcen zu erreichen.* Dieser Ansatz wird von einer Ingenieursperspektive gesteuert, und wird ergänzt von Graphischer Datenverarbeitung und Semantischen Technologien.

ABSTRACT

There are still many open questions and needs in important aspects of the scientific area of *Large Model Visualization* –LMV- *for Plant Design.* Performance to achieve interactive rates in immersive virtual environments is certainly one of them, especially if resources are limited, but not anymore the most critical one. Surprisingly, the different processes used today to generate the walkthroughs experiences take into account very few explicit semantic considerations. The main approaches presented in the literature in the field of LMV are mainly related to algorithms and compression methods to be applied to the geometric entities that compose the CAD model. However, no sufficient attention is given to the following aspects: (i) These models actually belong to a special engineering domain with related standards; (ii) the different potential users have diverse backgrounds and intentions; and (iii) an adapted visualization walkthrough of the model can be different for a specific user and purpose in that context, in order to use in an optimal way the available resources and techniques.

Therefore, the most common situation is that the generation of visual walkthrough experiences is typically not aware (in proprietary systems with links to PDM the situation is better to some extent) that the 3D CAD model of a plant is actually just a geometric representation of a complex engineering system, and this knowledge is not sufficiently exploited in the generation of the walkthrough experience. The consequence is to have advanced VR environments for the interactive exploration of models of millions of triangles, that have little explicit use of the knowledge –and in many cases none- about the domain, users and visualization purposes involved.

As a result, the main motivation for the present work is focused on one of this research lines not sufficiently covered so far: The *explicit introduction of semantic aspects*, pushed from an engineering domain perspective –and strongly complemented with computer graphics and semantic technologies-, in the process of generating visual walkthrough experiences for specific users, visualization purposes and resources in the Plant Design domain.

To Maite, Hugo and my parents
They are the light, the strength, the reason.

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I am also very grateful to Prof. Dr. F.L. Krause for his time and dedication as reviewer of this thesis.

Maite, Hugo, my parents and friends would require another full thesis.

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...you will know what the several images are, and what they represent, because you have seen the beautiful and just and good in their truth.

Plato, The Republic. Book VII – The Myth of the Cave

1 INTRODUCTION

1.1 Motivation

Large Model Visualization (LMV) is a well researched area in Computer Graphics ([FKS96], [ALMA00], [BSG02], [BART03] [YOSM03], [CORR04]), but still with interesting open issues for research. The possibility to have interactive walkthroughs for the very large geometric datasets offers clear benefits, as it reduces design times and allows the engineers and designers to detect early potential construction problems that may appear, especially in the integration of several independent modules of the industrial plant. Indeed, this has been one of the application areas of Virtual Reality with more applicability to industrial needs. The efforts of the research community have been very fruitful in this regard, but still have challenges to solve in the future.

Today, the Design Review (and in less proportion, other tasks related with visualization and interaction) of the CAD models of industrial plants is a process in which the technologies of Computer Graphics have a clear path to maturity. Most large engineering projects of new industrial plants are now discussed and reviewed in different stages of the design using special VR set-ups for collaborative exploration of the model. A typical set-up is for instance a Medium or Large Screen Projection room, where engineers, managers and clients can have an immersive, interactive VR Walkthrough experience to explore in detail the three dimensional model of the plant. They can move at will through the plant, inspect potential conflicts between structural layers of the model, verify accessibility issues, etc. This scenario, which only very few systems and companies were in a position to use just a couple of years ago, is becoming more and more available and affordable. The exponential increase in processing power, and especially in graphics hardware, as well as the lower associated costs of software and hardware, is bridging this gap up to the level of providing interactive walkthrough experiences on workplace PC's for models which the research community considered almost intractable large models not so long ago. Even commercial companies and products such as Intergraph SmartPlant Review [INTG05], Plant 4D [PL4D05] , Vantage Plant Design Review [AVE05] , NavisWorks [NAV05], Mantra 4D [MNT05], etc. are now providing advanced visualization tools for walkthroughs of large models of industrial plants, either as separate tools or integrated into a Plant Information Management (PIM) system.

Interestingly, the main trend in research in the field of Large Model Visualization for Plant Design has been pushed by the Computer Science area in general, and Computer

Graphics in particular (e.g. the Walkthru – GigaWalk group of UNC-Chapel Hill , see [YOSM03][GOVI03][BSM02] and many others), not from the Mechanical or Plant Engineering fields. The advances in several areas of computer graphics such as rendering acceleration techniques, database and scene graph management, interactive collision detection, etc. have helped decisively to achieve the current status.

However, as mentioned before, there is still open room for research in significant issues. Performance to achieve interactive rates in immersive virtual environments is certainly one of them, especially if resources are limited, but not anymore the most critical one. Surprisingly, the different processes used today to generate the walkthroughs experiences take into account (both in research and commercial products) very few explicit semantic considerations. The main approaches presented in the literature in the field of LMV mainly related to algorithms and compression methods to be applied to the geometric entities that compose the CAD model ([ALMA00][BSG02]). However, no sufficient attention is given to the following aspects:

(i) These models actually belong to a special engineering domain with related standards.

(ii) The different potential users have diverse backgrounds and intentions.

(iii) An adapted visualization walkthrough of the model can *–and one might even say "should"*- be different for a specific user and purpose in that context, in order to use in an optimal way the available resources and techniques.

Therefore, the most common situation is that the generation of visual walkthrough experiences is typically not aware (in proprietary systems with links to PDM the situation is better to some extent) that the 3D CAD model of a plant is actually just a geometric representation of a complex engineering system, and this knowledge is not sufficiently exploited in the generation of the walkthrough experience. The consequence is to have advanced VR environments for the interactive exploration of models of millions of triangles, that have little explicit use of the knowledge –and in many cases none- about the domain, users and visualization purposes involved.

As a result, the main motivation for the present work is focused on one of this research lines not sufficiently covered so far: The *explicit introduction of semantic aspects*, pushed from an engineering domain perspective –and strongly complemented with computer graphics and semantic technologies-, in the process of generating visual walkthrough experiences for specific users, visualization purposes and resources in the Plant Design domain.

1.1.1 Short Overview of the Technical Context

An important part of the Plant Design process is the generation of the 3D CAD model. The model geometry is usually stored in CAD formats and is later used as a base for advanced visualization and interaction tasks, in particular in interactive walkthroughs for different purposes, such as:

(i) Design Review of the model [GBS02], in order to find possible errors in early phases of the design.

(ii) Teamwork discussions about details and alternatives [ACW98], [CBK04], [HKC03].

(iii) Presentation for managers and customers.

(iv) Dissemination to the general public.

Understanding and interpreting very complex CAD models of industrial plants in their native modelling software is still a hard-to-master task for professional engineers and is nearly impossible for non-expert users. Most people who have been working with CAD systems have faced the problem of proper interpretation of CAD models. In many cases, it is not easy to understand what is represented in a CAD model. The more complex a model is, the more difficult it is to achieve a correct visual representation. Sometimes the abstraction level required to understand what is displayed on the computer screen is bigger than the user's capabilities [PLS02]

Most of the CAD packages do not produce themselves satisfactory interactive 3D walkthroughs for Plant Design, due to the complexity of the models and the limited resources available on common workplace computers. CAD to VR conversion, triangulation, data reduction, etc. has to take place to allow for interactive walkthroughs in complex scenes. This is the basis of most specialised software in the field: the conversion and optimization of the 3D CAD geometry representation of the plant, which almost entirely a tessellation-based process; only in few cases some structural information and relation to non-geometric data is considered.

Several researchers have addressed the visualization of large CAD models in VR; mostly on specialized hardware set-ups but sometimes even on PCs. (see section 2.1 *Large Model Visualization for Walkthroughs*). A common characteristic in Large Model Visualization of Industrial Plants is to work on the basis of the tessellated model by applying advanced CG techniques, e.g. advanced LOD and culling techniques, such as presented in GigaWalk framework, which is a clear reference in the field [BSG02].

Not so long ago, the main problems in the area were posed by *performance issues of the available resources*. There was a large of geometric information in the tessellated models, and it was impossible to render them interactively with the available resources without very advanced rendering and simplification techniques. In a reference SIGGRAPH course in the area [ALMA00], Manocha even explicitly says in the introduction that *"the complexity of large geometric datasets appears to be growing at a faster rate as compared to the rendering capabilities of the graphics systems."* However, this phrase has to be put in the appropriate context: in my experience the breach between tessellated model size and available resources is actually *decreasing in most practical cases* (at least in the engineering context of Industrial Plant Design), although there have been always new leading-edge models surpassing the capabilities of modern resources. Just to give a practical example of this fact, the coal-fired power plant (15 million triangles) still shown by his group [YOSM03] just two years ago as a reference large model, could be rendered in 2004 in almost acceptable rates for interactivity (4 fps) just using a consumer-class PC

(1 Giga RAM, 2 GHz CPU) new OpenGL extensions for vertex-clustering, and hardware occlusion culling hardware embedded the newest GeForce cards [NUYD02]. Fraunhofer IGD reports also in that year results with a ship model of 10 million triangles at 10 fps with an nVidia 6800. The performance of graphics hardware has just exploded; the newest nVidia GeForce cards (GeForce 7800, June 2005) can render up to 830 million vert/sec**.** It doesn't mean however that Manocha estimation is wrong: his example on the Boeing 777 with 2 million parts and 500 millions polygons is still a challenge model even for the best research approaches, not to mention commercial software; although it has been reported in [DIWS04] that a similar model of a Boeing 777 with 350 million triangles could be rendered using a real-time ray tracing approach. Also, as pointed out in [BART03] and [BART01], there are indeed models in the computer-aided engineering (CAE) domain with tessellated, polygonal models of up to 100-500 million polygons. But, for practical purposes, and especially in the Plant Design domain, the breach is clearly decreasing, since most real-world complete plant models have a polygonal tessellation *in the order of magnitude of 5-40 million triangles*. Other domains (submarines, airplanes, scientific computing, multislice CT data, etc.) are clearly in a different range (terabytes). Thus, the research community can, and should, also tackle interactive visualization problems of a different and complementary nature for that domain. A good example of this evolution is the emerging possibility to explore the synergies between advanced computer graphics techniques and semantic technologies for innovative approaches in the visualization of large Plant Design CAD models.

1.2 Problem Statement and Objectives

This research is focused in the context described in the previous section. There is a need to improve current visualization and walkthrough systems for Plant Design models with semantic aspects, in order to (i) give the user a better visualization which considers the domain, his background, and the visualization purpose; (ii) make a better use of the available resources in restrictive conditions using semantic compression techniques, (iii) provide a common framework to handle heterogeneous 3D CAD models in the domain, and (iv) give the basis for future fields of application in visualization walkthroughs, such as functional analysis of the plant components. Thus, the main objective of this work is the *semantic-based generation of visual walkthrough experiences of CAD models in the Plant Design domain*.

The following questions are closely related with this objective: Which kind of engineering components are represented by the geometric objects of the CAD model? Why is a user interested in a visualization walkthrough of an industrial plant? What is his background and how this affects the visualization? Is it feasible to increase the explicit semantic content of a 3D CAD model of an industrial plant, for better and more rational computer treatment and adaptation of the visualization walkthrough? Is it possible to take advantage of a more explicit knowledge about these aspects -user, domain, purpose-, in order to provide better interactive walkthroughs of industrial plants in a given context?

In order to contribute to this emerging research theme, and give an answer to the proposed questions, this work sets the following objectives:

- *Identification of the semantic aspects involved in the adaptation of a 3D CAD model of an Industrial Plant for visualization walkthrough experiences in virtual reality (VR) environments.*
- *Conceptualization and design of a general, extensible, modular methodology for adaptation of 3D CAD models of Industrial plants for VR, which can explicitly support and exploit semantic aspects.*
- *Research on the use and integration of domain related standards in the methodology to achieve generality and robustness.*
- *Development of an underlying mathematical model for the methodology that gives objective parameters to optimize available resources and rendering techniques, with semantic considerations of all aspects of the involved process.*
- *Investigation on alternative, symbolic representations for engineering components integrated the 3D walkthrough experience, as a potential complement to the accepted geometric accuracy paradigm.*
- *Implementation of a proof-of-concept software system that shows the effectiveness and validity of the proposed methodology with application to several real-world models of Industrial Plants.*
- *Evaluation of the impact of the proposed methodology with different real world models and users.*

The lines of research described above are the conducting thread of this work. The structure of this thesis corresponds closely with these research lines.

1.3 Summary of the Main Results

In the scope of this research, a new methodology has been developed in order to introduce semantic aspects in the visualization walkthroughs of large CAD models of Plant Design.

The next list is a summary of the main contributions and results of this research work:

- The conception of a general methodology for the semantic-based visualization of 3D CAD models of Industrial Plants for Virtual Reality walkthroughs, which considers the user profile, the visualization purpose and the optimization of the available resources and techniques.
- The implementation of a complete, integrated software system -the ***MiroWalk*** system- which follows the proposed methodology and has been extensively tested with several real-world models in the domain of Plant Design.

- The development of an orthogonal approach for the *enhancement* (instead of the replacement) of existing visualization walkthrough technologies from the Computer Graphics community to include semantic aspects.
- The application of emerging semantic technologies, especially ontology modelling and querying tools, in the innovative context (for those technologies) of the visualization of industrial plants.
- The inclusion in the methodology of a standard in the domain (the ISO-STEP 10303-AP227 standard) which helps in the disambiguation and classification of the geometric elements in a 3D CAD model of a plant design, independently from the proprietary packages used for the modelling.
- The definition of a mathematical model in the form of an optimization problem that controls the available resources and rendering techniques in a visualization walkthrough scenario considering the semantic aspects involved.
- The evaluation of the system with actual engineers and designers using real models. This last point has also originated new lines of research, as for instance the migration of the proposed methodology to the steel detailing domain using the CIMSteel Integration standard (CIS/2) as basis.

1.4 Structure of this Work

In the present work a semantic based methodology for the adaptation of industrial plant CAD models to virtual reality walkthroughs is presented. The enumeration at the end of this section gives an overview of the content and structure of each individual chapter. Some relevant background aspects are given in Chapter 2. The influence of semantic aspects for the large model visualization of industrial plants is presented mainly in Chapter 3. Chapter 4 explains the underlying mathematical model for the methodology. Chapter 0 is devoted to the description of architecture for the adaptation for semantic visualization walkthroughs of 3D CAD plant design models, including implementation aspects, and Chapter 6 is dedicated to present the results of the software system based on the proposed methodology. The conclusions and future work are presented in Chapter 7, whereas the publications derived from this research, as well as the bibliography of the research community used in this work, are presented in Chapter 8. A more detailed description of each chapter is given below.

- **Chapter 2 (BACKGROUND AND RESEARCH THEMES)** is dedicated to give the necessary background in the field, and to identify the most relevant research themes involved in this work.
- **Chapter 3 (SEMANTIC ASPECTS IN THE LARGE MODEL VISUALIZATION OF INDUSTRIAL PLANTS)** explains how different semantic aspects can be useful in the large model visualization of industrial plants in VR walkthroughs, with due consideration to standards in the domain, user background and interest, and available resources and rendering techniques.

- **Chapter 4 (A MATHEMATICAL MODEL FOR THE SEMANTIC ADAPTATION FRAMEWORK)** develops a simple but effective mathematical model directly related with the different processes of the methodology and modules of the architecture, in which the available resources and rendering techniques are optimized according with constraints associated with the semantic aspects of the walkthrough visualization.
- **Chapter 0 (**
- **GENERIC ARCHITECTURE AND SYSTEM IMPLEMENTATION OF SEMANTIC VISUALIZATION WALKTHROUGHS FOR PLANT** DESIGN**)** gives a detailed description of a general, semantic-based architecture with different modules involved in the process of adapting a 3D CAD model of an Industrial Plant to a suitable model for a VR walkthrough experience.
- **Chapter 6 (RESULTS)** is devoted to results and evaluation aspects of the proof-of-concepts software system which was developed following the proposed methodology.
- **Chapter 7 (CONCLUSIONS AND FUTURE WORK)** gives a synthesis of the main conclusions derived from this work, and points new directions for future work from the applied research perspective.
- **Chapter 8 (BIBLIOGRAPHY AND RELATED PUBLICATIONS)** provides an overview of the scientific references consulted as well as the scientific publications originated from this work.

2 BACKGROUND AND RESEARCH THEMES

2.1 Large Model Visualization for Walkthroughs

One important area in the Computer Graphics research has been the interactive visualization of large models. In this section I present some of the general aspects related to this field. It is difficult to find an agreement in the research community about what a "large model" is; however, a good definition has bed suggested by the developers of the original *Jupiter* toolkit library: *a large model is a model that can not be rendered directly since it exceeds the graphics capabilities of the available resources* [BASS01]. [ALMA00] points out (although this statement is less fortunate since it is indirectly tied to the HW capabilities at a point in time, four years ago) that a large Geometric Dataset is composed by millions of primitives. Whatever definition is chosen, it is clear that in recent times, the area of Large Model Visualization (LMV), also called Large Scale Data Visualization, has acquired an increasing relevance in the scientific community: data coming from several application domains are quickly growing in size and complexity e.g. in the medical area (PET/MRI data), in the Geographical Information Systems field (terrain, satellite images, etc.), in the architectural field, and of course, in the engineering domain (complex designs of products or facilities, design review).

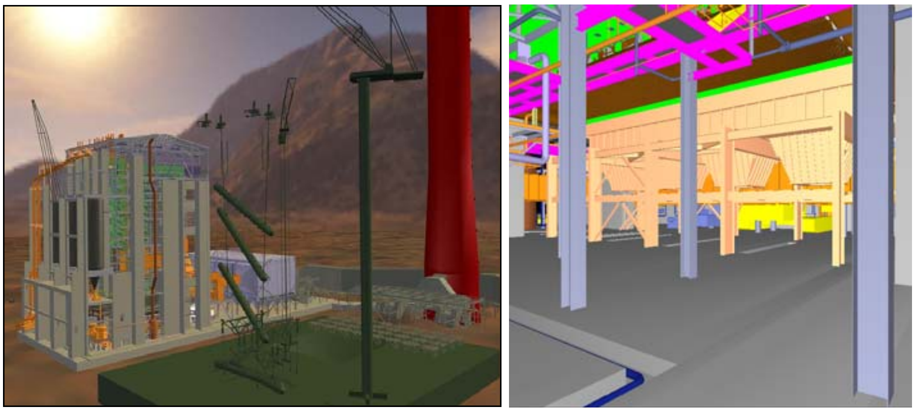


Figure 1. Example of a Large Model of Industrial Plant: the UNC Power Plant model with 15 million triangles (images taken from [BSG02][CORR04])

Several techniques have been developed to cope with the interactive visualization and interaction on 3D large models. For instance, in the case of medicine, advanced volume rendering techniques for massive medical data have been developed, as in [BART01]. With similar approaches, complex data sets of CFD and similar engineering data can be rendered, suitable for visualization and interaction in VR environments. In the GIS field, also important developments towards 3D interaction on large geographical databases have been developed [ZHCO04].

In the scope of this work, the most relevant topic regarding large model visualization is the research area of *interactive walkthroughs of large models.* As pointed out by Manocha in a classical SIGGRAPH course [ALMA00], there are basically four families of topics to consider in the interactive walkthroughs of large models :

i) Rendering acceleration techniques

ii) Database management issues

iii) Interactive collision detection

iv) System integration.

There is a quite similar exposition in [BASS01] with a slightly different formulation: according to it, the main rendering techniques focus on database management, architectural aspects of large computing systems, parallel computing, and the most important aspect, rendering techniques for visualization.

Several authors have explored the main rendering acceleration techniques with good results so far. As well explained in [BSG02], and extended in [COCD03] the main acceleration techniques used can be classified in few basic classes. I explain shortly these classes, with references to more comprehensive treatment of each class, as well as some of the challenges still open for them:

i) Culling (occlusion / visibility)

Occlusion culling methods attempt to quickly determine a *Potential Visibility Set* (PVS) for a viewpoint by excluding geometry that is occluded. I will not go into the details since the present work is not focused on this area. A good recent survey can be consulted in [COCD03]. Some new techniques are also introduced in [YOSM03] and [GOVI03]

While possible for certain environments, performing exact visibility computations on large, general datasets is difficult to achieve in real time on current graphics systems. Furthermore, occlusion culling alone will not sufficiently reduce the load on the graphics pipeline when many primitives are actually visible [BAX00].

ii) Geometric simplification

Simplification algorithms compute a reduced-polygon approximation of a model while attempting to retain the shape of the original. It is also called *polygonal simplification*.

Geometric simplification techniques e.g. Levels of Detail (LOD) - *static / dynamic / view dependant*- and Hierarchical Levels of Detail (HLOD) [LURC02] give good results in handling massive data sets. The integration of LOD and good occlusion culling techniques are usually the key factors to achieve interactive rates in walkthrough systems [ASN00] [ERM00]. Other geometric simplification techniques, such as Decimation, Progressive Meshes [SBSL04][HOP96], Vertex Clustering, Simplification Envelopes, Hierarchical Dynamic Simplification (HDS) and geometry compression, are also important in this regard. A very good survey of these techniques can be consulted in [LUEB01]. Spline Models, suitable for static or dynamic tessellation, can also be considered in this category [ALMA00]

The main problem of object based geometric simplification is that it alone has difficulty with high-depth-complexity scenes, as it does not address the problems of overdraw and fill load on the graphics pipeline.

iii) Image-based representations

An alternate simplification method is to replace complex geometry with images using texture mapping (often supported directly by graphics hardware), 3D image warping, etc. Images can be displayed at a rate dependent on screen size and independent of model complexity. There is a good amount of work in the automatic replacement of certain objects (e.g. far away objects) with texture-mapped polygons, referred to as *impostors*. Also, image based methods do not use polygons but photos or computer generated images for the navigation through a scene. Often new images are computed by interpolating two or more existing 2D images, with the advantage that they are independent of the scene complexity and thus they can visualize scenes of arbitrarily high quality with constant running time. The disadvantages however are the high memory consumption and possible perspective distortions. For more details and comprehensive references, the reader is invited to consult [ZHCH04] and [CUKK02].

There are some promising image-based algorithms, but generating complete samplings of large complex environments automatically and efficiently remains a difficult problem. The use of image-based methods can also lead to popping and aliasing artifacts.

An important issue to consider is how the resources of the system should be scheduled and managed. The budget rendering work of [KLOSI99] and the scheduling policy presented by Faisstnauer [FSP00] are entry points to this field.

A more recent development in Large Model Visualization which is not explicitly addressed in these categories is the Point Based Rendering of complex models, in which the primitives used for rendering are not anymore polygons but points. See [ALGP04] as the most updated and comprehensive information source. It is still to be shown if this development is suitable applied to walkthroughs of large engineering models.

To finalize this section, the reader is invited to study one of the most recent, complete scientific work of relevance in the visualization of large polygonal models, related with (but not only) to walkthroughs: it is the development of out-of-core visualization techniques made in Princeton [CORR04]. He points out that the *available memory* is nowadays a critical factor since the increase of memory is not growing at the same pace than models size, and develop new techniques able to visualize large polygonal models (even up to some billion triangles) at interactive rates with clusters of 8 PCs.

Each one of these main classes has been investigated thoroughly in multiple approaches from research, either independently or in a combined manner. In the evolution of the scene-graph based graphic APIs, many of these techniques have been explicitly integrated. The SGI Open Inventor was probably the first one, and is still a widely used scene graph API which has evolved towards a commercial variant from Mercury Systems, and the open source variant of Coin3D. IRIS Performer, OpenGL Optimizer, Jupiter, Fahrenheit (failed initiative), [BART03], and currently Open SceneGraph, and conspicuously **Open SG** [REVB02] have followed a natural path towards the integration of many of these technologies in APIs for general use (without specific domain considerations) providing excellent support for large model visualization of polygonal tessellated models.

2.1.1 Some Considerations about the Latest Evolution of Graphics Hardware

During the last years quite a lot of progress has been made in real-time visualization of large engineering models. On the one hand more and more powerful graphics hardware and on the other hand new sophisticated software techniques have propelled visualization capacities into new dimensions. Additionally, a great deal of know-how in geometric description and compression of the models has been accumulated.

An unexpected radical improvement of consumer graphics hardware during the last years –mainly driven by the computer-game industry– suddenly makes visualization of large models possible on low cost hardware. The development of 3D-hardware over the last years easily outperformed Moore's Law (see Figure 2). This exponential improvement has continued over the past few years, with a spectacular increase in GPU performance from **5 Transformation Mtris/sec** in July, 2000 (GeForce 256) to **780 Transformation Mtris/sec** in May, 2004 (ATI X800 XT) [LAST04]. This is a **52** times increase in less than 4 years. The new GeForce 7800, release in June, 2005, performs even much better, with 860 million verts per second [NVID05].

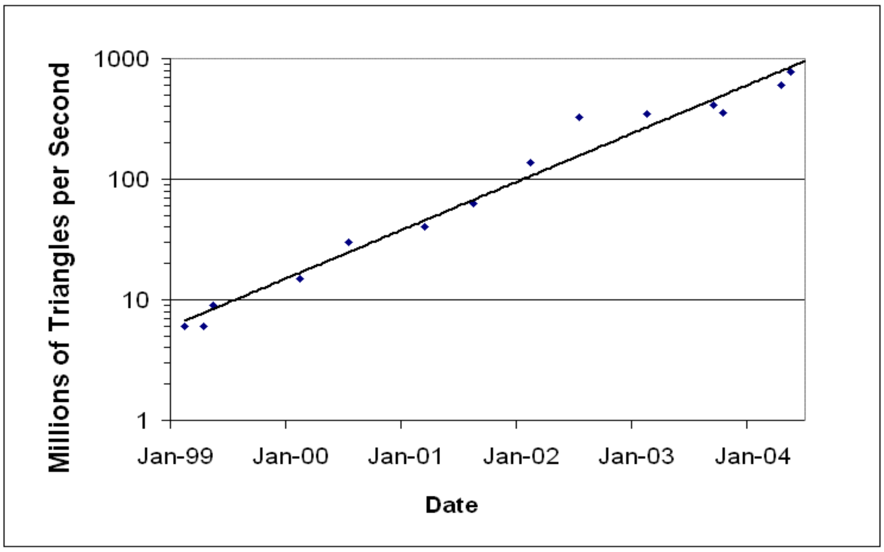


Figure 2. Development of GPU Performance (1999-2004). An exponential growth in Transformation Mtris/second has happened in last 5 years. Source [LAST04]

This evolution clearly shows that although some polygonal tessellated models in the M-CAD area are still very large, and increasing [BSG02][BART03], the performance of the graphics cards is increasing at a very fast rate, and suggesting that eventually, for that domain, it will be possible to render directly (with graphics hardware) most models. Of course, such spectacular improvement would not be possible without the HW support of many of the algorithms and techniques developed previously in this research area.

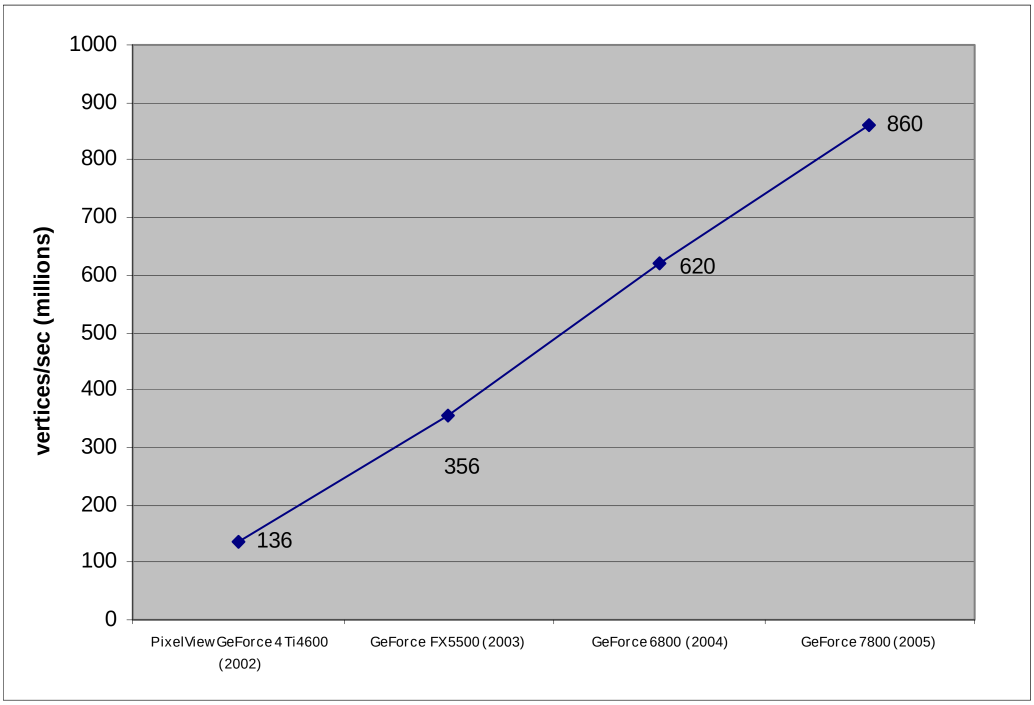


Figure 3. 3D Rendering Performance of graphic cards – peak performance in vertices/second (2002-2005). Compiled from different sources.

There are indeed models in the computer-aided engineering (CAE) domain with tessellated, polygonal models of up to 500 million polygons and more. But, for practical purposes, and especially in the Plant Design domain, the breach is clearly decreasing, since most real-world complete plant models have a polygonal tessellation *in the order of magnitude of 5-40 million triangles*. Other domains (submarines, airplanes, scientific computing, multislice CT data, etc.) are clearly in a different range (several billions of triangles).

Thus, the research community is now in a good situation to start exploring alternative and complementary problems, besides the pure Large Model Visualization, for the interactive visualization of engineering models.

It is in this context where this work focuses. There is an increasing need of enhancing the generation of walkthroughs experiences with semantic aspects, with a global perspective of the process, and involving not only the available resources, but also important aspects about the domain, the user and the purpose of the walkthrough.

2.2 3D Walkthroughs for Design Review in Plant Information Management Systems

Interestingly, the walkthrough of 3D CAD Industrial Plant models has been a reference area for the research on large model visualization. The best reference in this sense is the work of the University of North Carolina at Chapell-Hill [VAM02][BSG02]. However, in order to have a broader perspective, it is necessary to give a short background regarding that application domain, and beyond the computer graphics core algorithms.

2.2.1 Plant Information Management (PIM) – Relation with Product Lifecycle Management (PLM)

The CAD model is usually just one piece of a vast amount of data created during the plant design- and planning-process. This data includes part specifications and parts catalog, CAD drawings and engineering models, engineering analyses, purchase orders and change orders, process plans and routings, project plans, multimedia data, and all the other documentation created by engineering and manufacturing [GOUL03]

The sheer amount of data and the typically large size of workgroups for engineering projects usually create all kinds of problems synchronizing and managing the engineering data between the different members and the different departments involved. PDM (Product Data Management) systems try to address these problems dealing with engineering data and its relations throughout the *production lifecycle management* (PLM). Important companies such as UGS offer today a variety of products for PLM. It can be said that PDM is for the world of engineering what ERP is for the business world. The high-end CAD systems such as CATIA from Dassault Systems or ProEngineer from Parametric Technology Corp. are already integrated with their own PDM systems. In the world of Plant Design these systems are called *PIMS systems* (Plant Information Management Systems) [BOW99].

Proprietary plant visualization systems like Bentleys AutoPlant Explorer [BEN05] or Intergraph's SmartPlant Review have access to this additional engineering data in the PIM system and successfully take advantage of this to provide superior interactive visualizations for design reviews. However, often only the geometric CAD model is accessible, since the link to the engineering data has been lost. Loosing links to engineering data can have many reasons. Some of them are:

- Conversion for data exchange between companies or departments,
- Proprietary closed interfaces,
- Data coming from legacy systems,
- Exported data, etc.

2.2.2 Need of 3D Walkthrough Systems for Design Review

Some commercial, professional PIMS have their own module for 3D exploration walkthrough of the plant (e.g. SmartPlant 3D for Intergraph PDS), or agreements with specialised software companies. This need has been identified as critical for Design Review and other purposes related with the design and even operational aspects of the plant.

Although a vast selection of software for visualizing CAD models is available on the market, several of companies let outside providers create visualization of their CAD projects. In the Plant Design sector this is still a common practice, especially when the models involved are very large and complex. These companies are specialized on creating virtual reality scenes or animations out of CAD models. This practice is usually costly and leads to round trip times of several days or weeks. [WUND03].

The correction of planning deficiencies occurring during the construction, reorganization, or retrofit of a factory building is a time- and cost-consuming process. The high costs of correcting such mistakes, which often are not obvious before they can be seen on site, are one reason why design-reviews play an important role in the plant planning phase.

Detecting and analyzing those problems as early as possible is the key to minimizing these costs. For an early verification of the design, a 3D visualization of an Industrial Plant in a virtual environment can provide substantial support in the decision-making process. Appropriate visualization, navigation and interaction techniques have to be available in order to give a complete and realistic impression of the building in the best possible manner. Qualified statements of industrial key managers defending the advantages of 3D Design Review of their plants are enlightening: "*On two international projects in particular, we proved that 3D was the way to go. We detected clashes that would not have been noticed until the construction phase if the job had been done in 2D*" (Daryn Fitz, CAD Manager at Bovis Lend Lease) [NAV05].

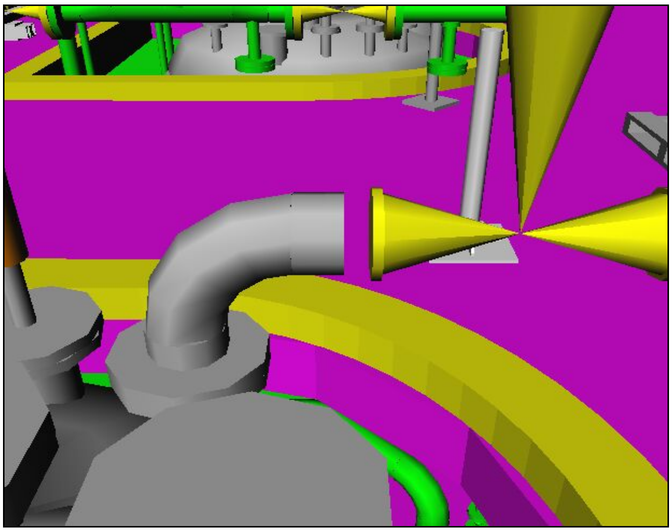


Figure 4. Real-World Example of a design problem detected in 3D design review: A missing flange between an elbow and a valve.

This fact becomes obvious when looking at a design flaw in 3D: while the slight displacement of an elbow-element in a 2D grid drawing may be easily overseen, a VR visualization of the same scene may show an apparent design error (see Figure 4)

An integration of a walkthrough visualization tool into the design process enables the designer to detect and analyze problems as early as possible. The visualization tool should preferably be directly integrated into the CAD environment the design-team is using. Thus, planning deficits can be determined and corrected in the early phase of the design process and mistakes can be avoided in advance, before the building is constructed.

2.2.2.1 Some Comments about existing Commercial Systems

There are several commercial systems now in the market for the evaluation, exploration and design review of industrial plants. There are basically two classes:

- *External tools that import 3D CAD models*
- *Integrated components in PIMS*

In the first class, emerging commercial applications (e.g. NavisWorks [NAV05], Mantra4D [MNT05], and Plant4D [PL4D05]) incorporate the latest graphics hardware accelerations as well as many of the classical culling and simplification techniques with good results. These specialised software products are able to read many common formats in the field, such as Bentley / Intergraph `dgn` format, AutoCAD `dxf/dwg` format, and even IGES or STEP models, in case available.

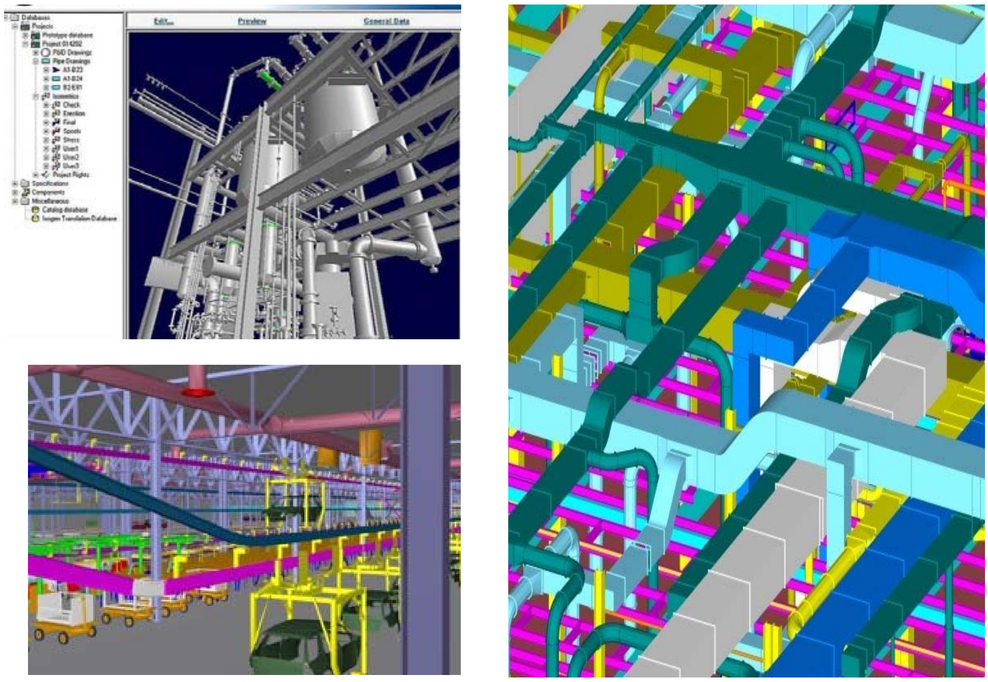


Figure 5. Screenshots of commercial systems with good *fps* performance in walkthroughs for small-medium models of Plant Design. upper left: *Plant 4D* lower left: *Mantra 4D* right: *NavisWorks*

These products can handle small and medium-sized models quite efficiently, with high rendering quality and limited support to structural information. Only in the case of pre-existence of a STEP model more domain specific information is provided; if not, merely *visual aspects* and in some cases collision detection during the walkthrough are possible. Figure 5 shows some screenshots of these representative tools. The walkthroughs do not take into account user profile or purpose, and only in few cases the domain.

On the other side, there are also tools integrated in their own PIMS. Examples of this kind are *SmartPlantReview* by Intergraph [INTG05], integrated in PDS; *VPD Review*, integrated in Vantage PDMS [AVE05] , Bentley *AutoPlant Explorer*, integrated in the AutoPlant solutions [BEN05], *DMU 4D Navigator* for CATIA V5 [CAT05] etc. These tools provide a much better link to PDM information since they have access not only to the 3D CAD data, but to all the underlying structural and PDM information, and actually make it possible to do a Design Review beyond the mere exploration of the 3D CAD data, with higher semantic content and context. However, there problems with very large models hold, as shown in the literature.

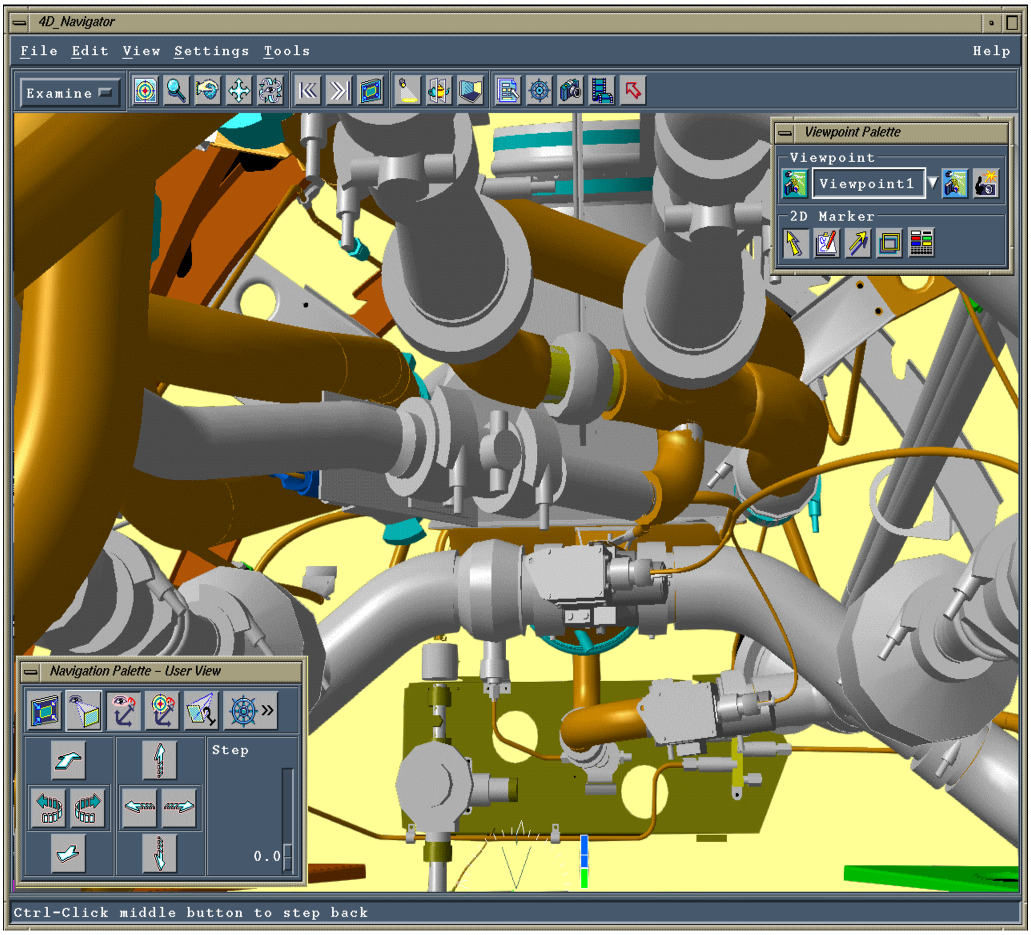


Figure 6. DMU 4D Navigator, CATIA V5. A high-end digital mock-up module of complex engineering models, integrated in CATIA PLM (from [CAT05])

Besides, the present work can still enhance the current approaches by adding a semantic dimension of users, model domain, and resources to the process of adapting the models for walkthroughs, either for Design Review -main focus- or for other purposes such as presentation to clients, accessibility studies, maintenance planning, etc. Figure 6 shows DMU 4D Navigator as a representative example of such systems.

2.3 Conclusions of this chapter

I have presented the current status of the two main background themes directly related to the present work: the classical Large Model Visualization area on the one side, and the Design Review based on 3D Walkthroughs for Plant Information Management (PIM), as an important part of the Product Lifecycle Management (PLM), on the other side.

2.3.1 Relationship between This Work and the Existing Background

This work is closely related with general research on Large Model Visualization, although with important specific aspects. As it has been shown in this chapter, walkthroughs of large datasets, among which industrial plants (e.g. power plants, pharmaceutical, chemical, and process plants) are important examples, has been a very fruitful research area in the last years, and is still a challenging area of Computer Graphics. Novel culling techniques, geometry simplification and image based representations are the families of rendering techniques more important in the area. Also out-of-core rendering techniques, database management and scene-graph optimization are key subjects for research.

Nevertheless, it has been shown that there are significant, particular issues to be carefully considered in the Plant Design domain. Although current trends in large model visualization research have a more general nature, where the common denominator is to work on achieving interactive rates of 5 to 20 frames-per-second, for the Plant Domain the classical basic problem of rendering complete 3D CAD models at interactive rates is not anymore the main issue (although it is still a very important one). Indeed, advanced research projects and commercial software are able today to handle most real-world models well enough to be of practical use in this field. On the other hand, it seems clear that specific aspects of the domain have not been considered in the main trend of research, especially the aspects related with the role of 3D Walkthroughs for Plant Information Management systems.

My approach explicitly includes semantic aspects regarding the domain of Plant Design, the user profile and background, and the purpose of the visualization walkthrough, in order to generate an optimized representation of the 3D CAD model in a VR walkthrough. In this sense, it complements both the areas of Large Model Visualization and Plant Information Management systems.

Next section will introduce the semantic approach underlying this work, including also detailed background information about related concepts and technologies.

3 SEMANTIC ASPECTS IN THE LARGE MODEL VISUALIZATION OF INDUSTRIAL PLANTS

The consideration of semantic aspects and technologies in traditional computer applications is a new possibility to increase on the one side accurate and meaningful information management and knowledge sharing, and on the other side reliability and performance (since explicit treatment of the meaning of the data and information can improve algorithmic solutions). The main advantages of this approach are the improved information management, searching and sharing, and the fact that the semantic data empowers the intrinsic knowledge of the elements described.

In the area of Plant Design, several PIM Systems (*Plant Information Management*) exist on the market, most of them following the conventional approach of providing separate tools to incrementally model the Plant through operations that allow the definition, modification, visualization and interaction with sets of basic parts. These systems typically include also some kind of Design Review and Visualization module for the 3D CAD Models generated as geometric representation of the model, also linked with PDM data and other supporting modules. This module can also be an independent, separate software tool.

In the conventional approach, this Design Review and Visualization module take advantage of traditional simplification and visualization techniques in Computer Graphics. To quote just two examples, algorithms of Level of Detail (LOD) are used to provide alternative representations of complex parts, and culling techniques are applied to avoid the processing of not visible parts, by high-end software packages intended for viewing massive data CAD models. In some cases, the mentioned algorithms are just not powerful enough as they lack of the relationships and intrinsic knowledge that a semantic tool is able to provide.

The methodology I propose in this thesis complements the purely geometric and graphic approach with **an additional dimension of semantics**, to provide better performance and task-oriented efficiency in the visualization process of the 3D CAD models. The approach is based on a methodology that explicitly takes into account the involved semantics in the process, including the use of the **ISO-10303 STEP –AP227** standard, as basis. This chapter explains the way in which semantic tools and models are involved in the process.

3.1 Short comment about the evolution of Ontology-based Applications

In recent years, considerable progress has been made in developing the conceptual bases for building technology that allows the reuse and sharing of knowledge. Ontologies are now used in Knowledge Engineering, Artificial Intelligence and Computer Science, in applications related to knowledge management, natural language processing, e-commerce, sharing of information in engineering [SSSP05a], information retrieval, database design and integration, bioinformatics, education and in new emerging fields like the Semantic Web.

Probably the fields in which computer-based semantic tools and systems are more extended nowadays are ***Ontology based applications*** for several heterogeneous domains: medical (LinkBase), chemical (ChEBI. BAO), legal (LODE), cultural (CIDOC-CRM), etc., mainly focused in querying and classification purposes in Information Sharing and Knowledge Management contexts.

Let's recall shortly what ontologies are and what are they used for. In philosophy, ontology is the most fundamental branch of metaphysics. It studies being or existence as well as the basic categories thereof—trying to find out what entities and what types of entities exist. However, in the Computer Science domain there is a different definition. The following is a widespread accepted definition of what an ontology is in this context, proposed by Tom Gruber: *ontology* ***is the explicit specification of a conceptualization***; a description of the concepts and relationships in a domain [GRUB95] . It is true, however, that many researchers in the AI community start their publications with their own definitions of ontologies, but in short the definition above is well accepted. Ontologies are commonly used in artificial intelligence and knowledge representation. Computer programs can use an ontology for a variety of purposes including inductive reasoning, classification, a variety of problem solving techniques, as well as to facilitate communication and sharing of information between different systems. Also, emerging Semantic Web systems use ontologies for a better interaction and understanding between different web-based systems using agents.

In this last direction, a recent survey of ontology-based applications, with focus on e-commerce, knowledge management, multimedia, information sharing and educational applications, can be found in [RAGO04].

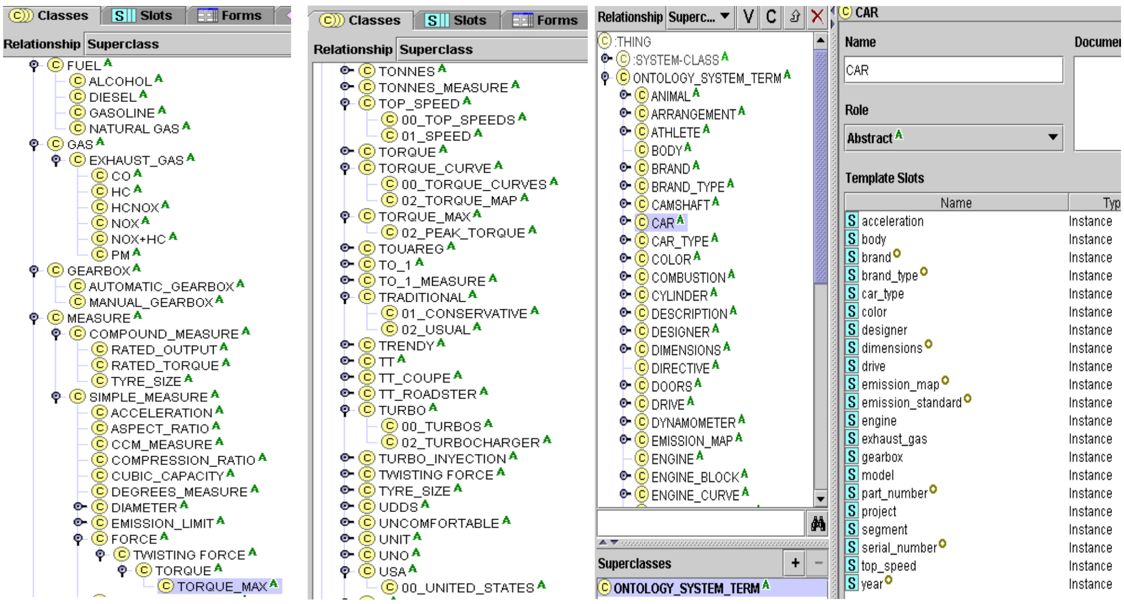


Figure 7. Excerpt of a domain ontology for engineering (The Domain Ontology of the IST-2001-24417 / EU Project WIDE – see [SSSP05a])

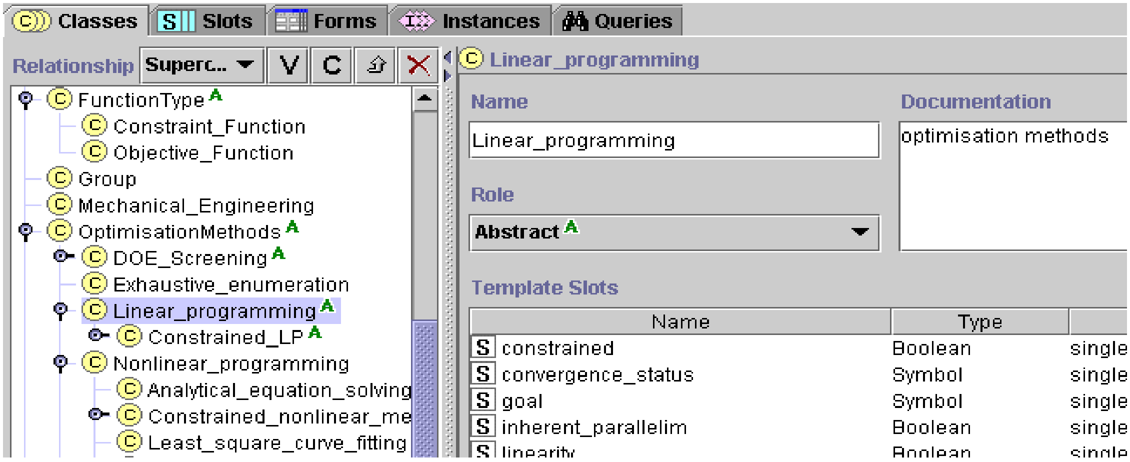


Figure 8. Excerpt of a domain ontology in the engineering design process supported GRID Applications (EU project GEODISE, [CHSH04])

The increasing success of the semantic techniques, mainly based on internal ontology modeling, is due to the effective support they provide for knowledge management and information sharing processes.

Software tools such as Protégé [PRO04] or Ontolingua [FAFR96] (among others) are used more and more to model domain specific ontologies, including a good amount of specialized modules or plug-ins to support the modeling tasks, and the use of accepted languages and specifications such as RDF, OWL and XML [SSSP05a] allow the traversal, querying, and interaction on the ontologies for applications with specific purposes. These tools and languages have been generated mainly from academic research, but they are gradually demonstrating that industrial use is also possible, although some limitations still exist regarding industrial strength requirements.

Figure 7 and Figure 8 show two excerpts of ontologies modeled with Protégé in different domains, but specifically focused in engineering design processes: collaborative car design, and GRID-supported design search in engineering.

The methodology proposed in this work is focused on generation of suitable models for visualization walkthroughs of Plant Design models, and makes use of existing ontology tools and technologies for modeling some of the semantic aspects related with the proposed methodology. Especially, the domain ontology (based on ISO-STEP 10303 - AP227), connected with the visualization purpose, user and resources ontologies, play a valuable role in the proposed methodology of this research.

3.2 Semantic considerations in the fields of Computer Aided Design and Product Lifecycle Management

In the field of Computer Graphics, the elements in a CAD drawing (2D or 3D) were until very recently just geometric representations of the designed object. Their internal structure was primarily based in simple basic geometric primitives such as curves, surfaces and solids.

The objects in some legacy CAD systems (but also in many modern CAD systems) were not aware of internal relationships, and more importantly, didn't have explicit semantics in the sense that they were not aware of their meaning in the domain, and were not *semantically* related with other objects and their context. In fact the most common relationships were usually (and this is still valid in some packages) joining or layering relations acting merely as hierarchical groups for organizational purposes. At the most, some relationships to Product Data Management (PDM) systems are available. In some cases information about use, relationships between elements, physical properties, function, etc. is well know by the designer, but it must be attached via an external sheet of specifications or bill of materials.

Some emerging research initiatives are exploring the explicit representation of knowledge in the design and modeling processes. Thus, with a semantic enriched approach, objects should not be anymore a collection of low level data whose meaning is actually only in the mind of the expert designer or engineer. Some good examples of the relevance of this approach can be found in some recent research projects cofinanced by the European Union. The European Project SPACEMANTIX (IST-2001-34159) [MAGA04] in which models in a domain (e.g. furniture) are explicitly related to each other from a functional perspective, with dependencies between them, and the European Project AIM@SHAPE (FP6 IST- NoE 506766) makes advanced research in the direction of semantic-based shape representations and semantic-oriented tools to acquire, build, transmit, and process shapes with their associated knowledge. A similar approach is also followed in the European Project SMARTSKETCHES (IST-2000-28169) [SGFS03] which helps designers and engineers during the shape definition phase with effective semantic support, oriented to the functional aim of the designed part where emotional and technical sketching considerations (from semantics of the domain) help to define sketches of products in 3D VR environments, preserving the restrictions and respecting product requirements. This research work, whose implementation is the Mirowalk system [PWTS04a], is also naturally related with the trend of including semantic aspects in the Product Lifecycle Management.

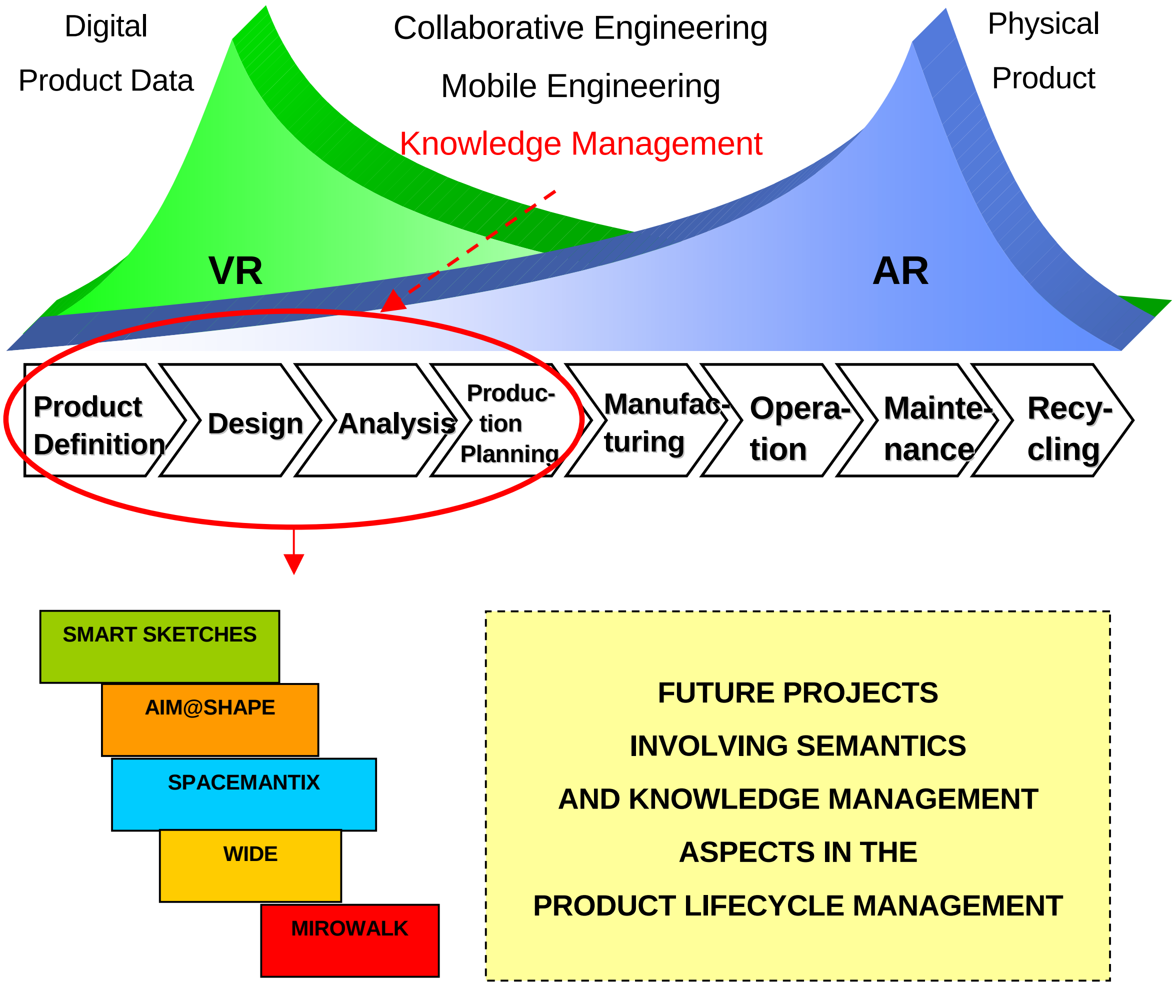


Figure 9. Influence of Semantics and Knowledge Management in some representative research projects in the Product Lifecycle Management for Virtual Engineering

Actually all phases of the design process could benefit from semantic enrichment. In the Figure 9, I show how these projects are focused on special phases of the design process, and how the semantic simplification system (Mirowalk) [PTWS05c] covers a different but complementary phase. I also follow a semantic approach in a special phase of the design process (especially in the Analysis and Production Planning phases), by allowing semantic simplification of large models for Design Review processes.

It's important to notice that there is a clear tendency in the research community to involve knowledge management and semantic aspects in all phases of the Product Lifecycle Management, initially focusing in the first phases, but with a lot of potential for further phases in the lifecycle [VALU03].

The strong relationship between the STEP standard and the ontology approach in the MiroWalk system is better described in chapter 3.5.

3.3 Semantics in the Large Model Visualization and Design Review

Large datasets in CAD Plant Design are difficult to handle not only for the computer but also for the person who have to understand the information that is stored in the model. Thus, the problem of management of large models has different sides: it is not only necessary that the computer can deal with the model but the visualization has to be easily comprehensible for the user. The model to deal with both sides of the problem is reflected in the following section.

It is true that high-end CAD systems have already excellent visualization tools, but several widespread CAD systems still depend on converting the model to a Virtual Reality format, such as VRML. When the models are not very big, these tools of direct conversion usually work acceptably well. However, this conversion process is not addressed with enough detail for Large Models in normal working environments. As a result, in many cases, the interactive visualization of such a Large Model fails, since it takes to the limit the resources of the computer (memory, processing power, etc.), making it unusable in normal circumstances.

A problem that usually appears is the ***loss of information*** during the conversion process to VR model. CAD models store a big amount of information, including (but not only) the geometrical and visual representation. Actually, in some cases, a relevant part of the dataset is invested in complementary information, not directly visible but very useful, such as the organization of the graphic elements in a level-tree or the information associated to the characterization of the different parts. In some CAD systems, after the conversion, a complete model becomes a *mere graphical scene* in which it is only possible to access the visual geometric information; the access to the rest of the information is only possible in the CAD format, so the VR model is not as useful as it could be.

An automatic (or better, semiautomatic) conversion to VR models is still a valid approach. But to do this conversion process well is still a problem, especially when usual workplace computers are concerned.

This kind of conversion typically considers two factors: the ***model characteristics*** (size, structure, complexity...) and the ***available computational resources*** (memory, processor, graphics...).

However, an important factor is sometimes neglected: What about the **final user**? What about the characteristics and capabilities associated to the user who has to interpret and understand the model? The user is a key factor in the conversion process that is usually neglected.

Conversion based on model and resources only, is “blind” to user needs and knowledge. Following the usual approach, optimizations are possible on the converted model, but they are “impersonal”, not oriented to the user of the final VR model. In fact, much knowledge is lost in the conversion process.

User knowledge and needs can bring semantics to the process, and allow a faster, better visualization for his purposes. Different users have different abstraction abilities depending on their training and education, among other reasons. The generation of the same VR model for all of them ignores this. It should be more appropriated to show only what the specific user needs to know in a way he can easily understand. For instance, the appropriate VR models of an industrial plant of for a manager, or for an engineer, are different; not only because of the kind of information both users are interested in, but because of the different information they are able to understand.

Thus, if it is not necessary to get a VR model suitable for everybody, it could be possible to define a conversion process in order to customize an **adapted** model that fit into the system resources and user requirements. Moreover, this can have the additional advantage of an increase in the performance of the visualization.

3.4 The Semantic Triangle Concept

Somehow it is more natural to think that the walkthroughs semantic enhancement should consider that ***model semantics*** can help in the conversion of CAD models to VR for a more efficient visualization of large models.

However, semantics are not only linked to the information objectively stored in the model itself, but to the *user* also. Actually I propose to include user knowledge in the process: to implement conversion and representations considering not only the graphical characteristics of the model, and the way the computer has to display them, but also the meaning and importance of the model for the user.

Thus, the three involved factors (including the resources) for the generation of an interactive 3D experience for Design Review are closely entangled and can be used to improve the walkthrough visualization with semantic considerations. I have introduced in this sense the ***Semantic Triangle*** concept, to make explicit the interdependencies between these three factors, in the Figure 10.

The basic concept of **Semantic Triangle** was already introduced in [PLS02], and it is an important basis for the full methodology for adapting 3D CAD models of Industrial Plant Design to VR Walkthroughs according to the methodology in which this research is based.

The Semantic Triangle can be regarded as a simple but powerful conceptual answer to the problem of involving semantics into the process of converting 3D CAD models of Plant Design to VR environments.

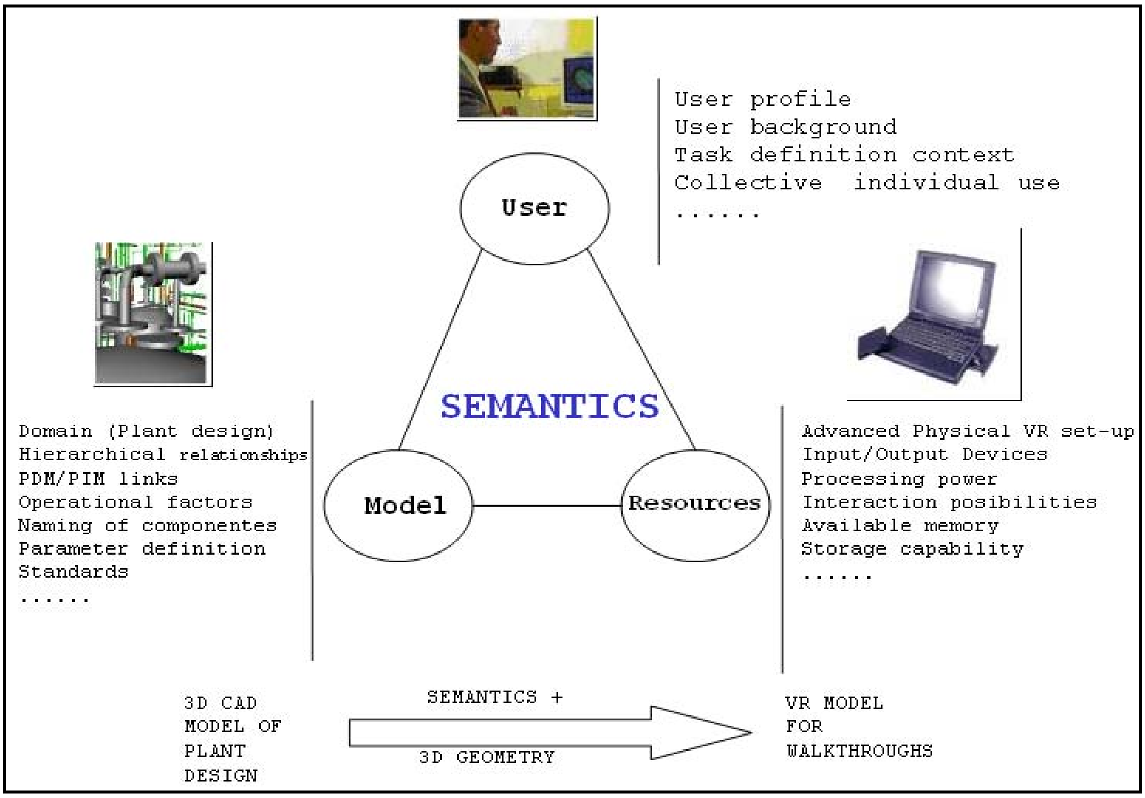


Figure 10. Semantic Factors involved in the adaptation of Industrial Plant 3D CAD models to Virtual Reality walkthroughs – User (profile/purpose), Model domain and available Resources

3.4.1 Model semantics

The semantic information stored in the CAD model is important in order to allow the maintainability, efficient management and conspicuously the exchange of product data. Perhaps the best effort in this direction in the CAD field has been the introduction of the **STEP** standard (**Standard Exchange for Product Data**, ISO-10303) [ISO01] [DBJ00], which has provided a standardized mechanism for expressing the product data and semantics for the purpose of exchange. This standard has been explored with various degrees of success in its integration with Virtual Reality environments. However, although the STEP representation can hold the comprehensive model semantics, the further conversion to virtual reality ignores in many cases important information, mainly tessellating the model and giving some links to non-geometrical data in the PDM systems.

Actually, one of the reasons for restricted interaction in VR for CAD models is indeed the **loss** of important model semantics such as the correct topological description of the objects.

The MiroWalk system exploits specifically this possibility (the relation with STEP standard) as a support for the proposed methodology, enhancing semantically the adaptation process of a 3D CAD model of an industrial plant for VR walkthroughs, with a focus on the domain (this is equivalent to the *model* node in Figure 10).

Shortly, it takes into account explicitly that the 3D CAD model belongs indeed to a clear, standardized domain: Industrial Plant Design. Specifically, the ISO-STEP Adaptation module in the architecture allows a mapping between the 3D CAD objects of the industrial plant and categories of the standard. A detailed exposition of the way in which model semantics are modeled in Mirowalk, based on the ISO-STEP 10303 standard, are found in Chapter 5.2. More details about the mathematical foundations for this process are found in Chapter 4.4.

3.4.2 User semantics

Semantics is associated to the user knowledge in all the stages of the model generation process: CAD model design, conversion and visualization. In the model design stage, user knowledge brings semantics at a low level by structuring the information in a layer schema, making well-structured design groups, giving meaningful names to the graphic elements or simply determining the version of the model, among other ways. At a higher level, in PIM systems, it is possible to explicitly define plant components and relationships, which unfortunately are not explicitly stored in the 3D CAD model representation, but in a separate, linked PDM system.

Actually, the user semantics is directly related with the ***visualization purpose context*** and ***user background*** in a specific walkthrough scenario. This approach is similar to the role user and task contexts are used in the European Project WIDE (IST-2001-34417) [SSSP05b].

This is the sense of the *user* node in Figure 10.The explicit semantics are the result of work that a user puts into the model during the design stage, for example by structuring the model into levels, naming and coloring parts, annotating parts with product information, etc. In order to make use of implicit semantics hidden in the model the user is needed to discover them. Additionally, the semantic information about the user who is going to view the VR-model is very useful. Different users have different abstraction abilities depending on their training and education, among other reasons. The user has a profession, certain knowledge about the domain and maybe about the model as well. He may be able to understand technical terminology, certain visualizations, symbols, language, etc.

Furthermore, the user may have a focus of interest (structural elements, inner parts, intersections, design layers). The ***purpose*** of interest for a user is also a key aspect to consider in the semantic adaptation process. The visualization walkthrough needs are very different, for instance, for an engineer with the purpose of a *Design Review*, or for a Manager with the purpose of a *Presentation to client*. Details about how ***user profile*** and ***purpose context*** are used in this methodology are found in Chapter 5.3.

3.4.3 Resources

Besides the already described model and user semantics, a third semantic component comes into play: the resources that are available to create and display the VR-model. These resources are the physical set-up used for the visualization walkthrough: (e.g. a workstation of a CAD Engineer, or the company's own low-cost CAVE system in the basement, or a cluster of PCs). The proposed methodology involves the available resources in the methodology, as explained later in Chapter 5.3. taking into account different resources (CPU, Memory, Graphics) so that it is possible to predict if the complexity of a model allows its visualization with the available techniques, taking into account the user and domain,

By using the term *resources* I do not only mean the resources that are available for displaying the model, but also the available hardware for the *adaptation* process (Figure 10). A quick work progress assessment within 5 minutes on the designer's computer monitor may need totally different processing power than the customer presentation at the end of the week on a large projection screen with the final client. The preprocessing time of hours and days needed in other projects [BSG02] [ACW98] shows that this is a factor that should not be ignored.

3.4.4 Explicit Semantics vs. Implicit Semantics

3.4.4.1 Explicit semantics

In this approach, I refer to *explicit semantics* when the knowledge can be extracted from related information already put by users in the CAD or PDM system during the previous modeling stage. **Explicit semantics** are the semantics that can be accessed directly from the model. Apart from the geometric and topological data that is inherent in CAD models, models often contain further information. This can be a layer-structure applied during the design phase, a hierarchical tree-like-structure that gives important topological information on how parts relate to each other or the still existent grouping information of cells inserted from part-libraries. Furthermore, parts of the CAD models may have been annotated with explicit information about their function, their specifications, bills-of-material data, domain specific data, etc. All this gives valuable information about the model.

3.4.4.2 Implicit semantics

On the other hand, I refer to *implicit semantics* when a ***user*** is necessary to identify and fully reconstruct the knowledge stored in the model: catalogue reconstruction, isolation of parts, removal of aids for model construction, importance of a specific part, etc.

Some semantic information of the model may not be stored in an explicit way, but it has to be identified using the *knowledge of a user* (or sometimes also through sophisticated algorithms). This is what I call implicit semantics. For example, the domain of a model (e.g. process plant or chemical plant) may be either stored explicitly using, e.g., STEP or be reconstructed through the knowledge of an expert user. Further examples are the reconstruction of a parts catalog, isolation of parts, removal of geometrical aids used during design phase, defining the importance of a specific part, etc.

The exploitation of both levels of semantics (implicit and explicit) allows a better Virtual Reality model, oriented to the user, who has introduced semantics and whose knowledge is required in the visualization walkthrough process.

The methodology of this research enhances the *explicit* semantics of the generation and use of visualization walkthroughs for Industrial plants, as explained in Chapter 0.

3.4.5 Semantic loss

Displaying a model of a plant in a virtual reality environment often involves converting it to a new VR-format. During the conversion process often only geometric information directly needed for the visualization is exported and a lot of the previously described **semantic information is lost**. Thus additional information like part annotations, links to PDM data, and topological structure is often lost at an early stage of the visualization process. In addition, exported models usually do not hold the parametric representation of primitives. A virtual reality system usually only supports a limited set of primitives. Primitives that are not supported by the virtual reality system must be mapped to substitute structures, loosing topological characteristics of the model. For example, several geometric primitives in the CAD system are not supported in virtual reality environments. This means that in order to view solid structures, they must be converted to NURBS or even tessellated to flat surfaces. This is an example of **model semantic loss**.

On the other hand, the CAD conversion to Virtual Reality is at a large extent done without any (or very few) participation of the final user in the process. Thus, a high degree of automation is provided, but all semantics related with the user needs and previous knowledge is neglected. Important aspects such as the purpose of the visualization (design review / presentation / interaction with elements / queries / etc.) and the focus of interest (structural elements, inner parts, intersections, design layers) are not considered in the conversion. This kind of information loss is what is called **user semantics loss**. Some of the typical semantic loss cases are shown in Figure 11: loss of hierarchical structure, parameter loss, part catalog loss, PDM attachment loss, relationship loss, loss of functional operators and loss of naming structure.

As a result of both model and user semantics losses, when advanced computer graphics techniques are used for visualization, they focus solely on *the tessellated model obtained by automatic conversion processes*.

The outcome is then as good as possible given this starting point, which has already important semantic losses. It is pointed out that **taking into consideration the semantics**

in the conversion process can bring a better performance for the visualization of CAD models, [PLS02] especially when they are very large and the resources available are not enough for a real-time visualization of the model otherwise.

3.4.6 Conclusions of this section

I have given in this chapter the conceptual basis for using Semantics in Large Model Visualization. With the introduction of the Semantic Triangle (Figure 10) and the considerations of Resources, Model and User Semantics, I have explained this multiple view on the walkthrough generation problem, beyond purely geometric considerations.

Also, with the basis of this semantic support, I have shown different approaches about how a system can exploit the explicit knowledge in different phases of the Product Lifecycle Management. In the next section, I explain in detail how the Mirowalk system follows the conceptual basis explained here by means of an ontology based on the STEP 10303-AP227 standard for Industrial Plant Design.

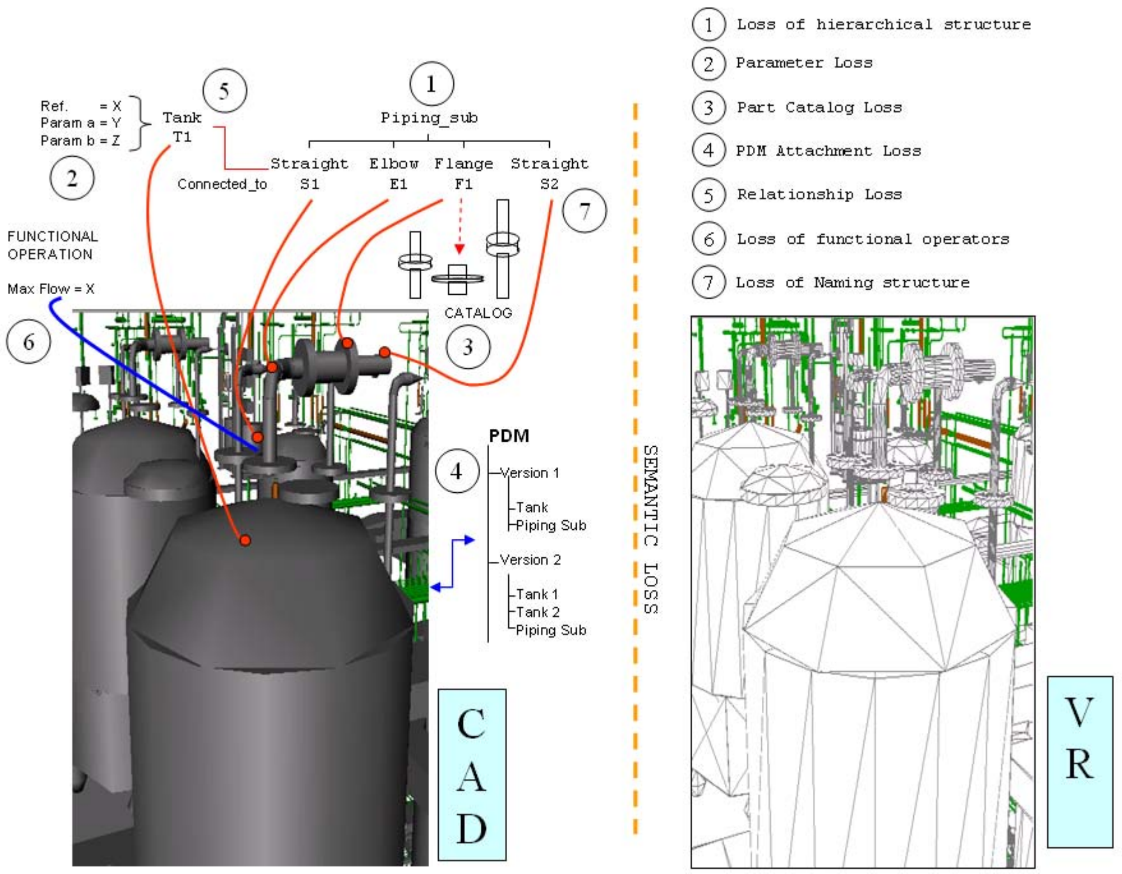


Figure 11. Semantic Loss in the conversion of 3D CAD Industrial Plant models to Virtual Reality for Visualization Walkthroughs

3.5 The ISO-STEP 10303 Standard and the Semantic Adaptation of Plant Design Models for Visualization Walkthroughs

In this chapter I will explain how the ISO-STEP 10303 standard is used as the basis to construct the Domain Ontology, which allows the implementation of the semantic steered conversion of 3D CAD Models of Plant design into effective visualization in Virtual Reality walkthrough scenarios.

3.5.1 Overview of the ISO 10303 STEP Standard

The official title of the ISO-10303 standard is *Industrial automation systems and integration - Product data representation and exchange* [ISO01].

However, ISO-10303 is commonly known as **STEP** or *Standard for the Exchange of Product model data*. It is an international standard for the computer-interpretable representation and exchange of industrial product data. The objective is to provide a mechanism that is capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving.

The core of STEP consists of a collection of *conceptual models*, which describe the content, and structure of product data items. ISO 10303 specifies a language by which aspects of product data can be defined. The language is called EXPRESS. ISO 10303-11:2004 [ISO04] also specifies a graphical representation for a subset of the constructs in the EXPRESS language. This graphical representation is called EXPRESS-G. EXPRESS is a data specification language as defined in ISO 10303-1. It consists of language elements that allow an unambiguous data definition and specification of constraints on the data defined.

The development of STEP started in 1984 as a successor of IGES, SET and VDAFS as a CAD exchange format. Whereas IGES was developed primarily for the exchange of pure geometric data between computer aided design (CAD) systems, STEP is intended to handle a much wider range of product-related data covering the entire life-cycle of a product. [PRAT01]

The most useful parts of ISO 10303, i.e., those parts defining models on which translators are based, are known as *Application Protocols* (APs). Each AP is applicable to one or more lifecycle stages of a particular product class. In 1994/95 ISO publishes the initial release of STEP as international standards (IS) with the parts 1, 11, 21, 31, 41, 42, 43, 44, 46, 101, AP201, AP203. Today, for instance, **AP203 (***Configuration controlled 3D design*) is the most widely supported part of the standard, since it deals mainly with the exchange of product shape models, assembly structure, and configuration control information for Geometry Data Exchange. Thus, many CAD systems use it for import and export, together with AP214 (which is similar but with a broader scope; it belongs to the automotive sector but is widely used in other areas too). With the second major release, which ended in the year 2002, STEP addresses specific needs of various industry areas (AP202, 209, AP210, AP212, AP214, AP224, AP225, **AP227**, and AP232).

The Application protocol AP227 describes the specifics for **plant spatial configuration** (Figure 14 shows an excerpt of the Express diagram showing the elbow and flange elements). This is the concrete application protocol of interest for this research.

STEP is developed and maintained by the ISO technical committee TC 184, Technical Industrial automation systems and integration, sub-committee SC4 Industrial data. Like other ISO and IEC standards STEP is copyright by ISO and is not freely available.

Application data according to a given data model can be exchanged either by a STEP-File, STEP-XML or via shared database access using SDAI. The top data models to be used for data exchange are defined in the APs and are based from lower level data models.

STEP is defining two different types of data models, the Application Integrated Models (ARM) and the Application or Module Integrated Models (AIM, MIM). The simplified and incomplete ARM models define application objects from a user's perspective. The MIM integrated models are based on a common set of generic objects, allowing interpretability between different kinds of industries and life cycle stages.

The numbering of the parts of this International Standard reflects its structure:

- Parts 11 to 14 specify the description methods;
- Parts 21 to 29 specify the implementation methods;
- Parts 31 to 35 specify the conformance testing methodology and framework.
- Parts 41 to 50 specify the integrated generic resources;
- Parts 101 to 107 specify the integrated application resources;
- Parts 201 to 237 specify the application protocols

  (*The part of interest for my work*)
- Parts 301 to 337 specify the abstract test suites;
- Parts 501 to 520 specify the application interpreted constructs.

As explained in this section, the most relevant part of the standard for the proposed methodology is:

Application Protocol AP227 – Plant Spatial Configuration (Editions 1 and 2)

It is very important to state clearly at this point that I *do not* intend to implement a traditional STEP translator in this methodology. See next section for more details about this relevant point.

3.5.2 Some comments about the scope of ISO-STEP 10303 AP227 in this research

At this point, it is important to state clearly that the motivation for the use of the ISO-STEP 10303-AP227 in this research is the following:

> *To use a standard in the specific domain -Plant Design-, which specifies the components and relationships that can found in a CAD model of an Industrial Plant, with the purpose of having a common, universally accepted, domain-specific reference, in order to associate some relevant geometric entities in a typical 3D CAD model of the domain, with the concepts of that standard. This allows a disambiguation of the geometric representation of the model, as well as the further semantic adaptation of the model for visualization walkthroughs.*

I have found that ISO-STEP 10303 AP227 fulfills these requirements very well.

As explained in the standard, there are four levels of implementation:

- Level 1: Passive file transfer
- Level 2: Active file transfer
- Level 3: Shared access database
- Level 4: Integrated knowledge base

But all of them focused on the *exchange* of product data. Notice that the objective of the present work is *not* to create a typical STEP translator between CAD models (Levels 1 & 2) or a data sharing framework (Levels 3 & 4).

Thus, I do not produce STEP-compliant physical files or typical STEP frameworks; I use the *concepts* and *relationships* described in the standard in EXPRESS-G language, adapted for the purposes of this research, and integrated with other concepts and relationships of resources, user profile, visualization purpose and rendering techniques. For this I have chosen to model ontologies as explained and in Chapter 5.3.

In doing so, I use indeed one of the key benefits of that standard, according to Fowler [FOW95]: "*one of the standard's key benefits is the availability, in the public domain, of world-class information on product data and product data modeling*".

This use of the standard is an integral part of the methodology of this research: to put in context, the role of the standard is to give a sound reference to process the output model of the *Catalog Reconstruction Module* in order to assign each family of geometric objects with a standard category, which can be used and controlled individually in the adaptation process. More details can be found in Chapter 5.2 *"The ISO-STEP 10303 Adaptation Module"*.

However, it is true that the increasing adoption of STEP export options by the PIM/CAD systems (AP203 is of widespread use, and some vendors are incorporating AP227, albeit slowly). This is an additional advantage to the proposed methodology; assuming that a CAD model of a plant can indeed be exported to a STEP AP227 physical file (not the general case now), the methodology is still valid and would work even better. This is equivalent to the first two processes of the methodology,

3.5.3 ISO STEP 10303- Application Protocol 227 - Plant spatial configuration

I use as a basis for the ontology modules related with the domain of Plant Design a specific standard: *the ISO-STEP 10303 Application Protocol AP227 – Plant Spatial Configuration* (Editions 1 and 2).

ISO 10303-227 is an application protocol for the exchange of ***3D Plant Design information***. AP 227 places emphasis on piping and HVAC (*Heating, Ventilation and Air Conditioning*) design and includes the physical and functional characteristics of the plant items and references to specifications and stream design cases.

This application protocol specifies the spatial configuration information of process plants which includes the shape, spatial arrangement and other characteristics of the plant piping systems. To point an interesting fact, this protocol is been used also for *ship design*, this is because of the similarities found in both application domains (especially in piping & HVAC components); and the fact that for the time being a specific application protocol for this domain is not available.

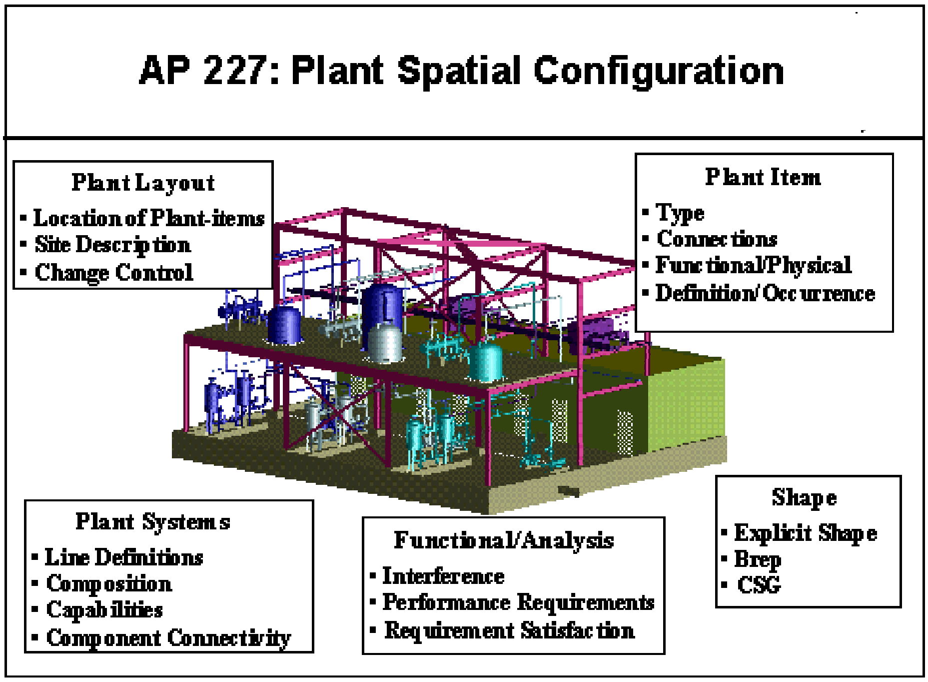


Figure 12. Overview of the ISO-STEP 13013 - Application Protocol AP227: Plant Spatial Configuration

The information in AP227 includes the shape and spatial arrangement characteristics of piping system components and other related plant systems (i.e., electrical, instrumentation and controls, heating, ventilation and air-conditioning, and structural systems) that have an impact the design and layout of piping systems. In the design and fabrication of a piping system, the piping layout must be evaluated with respect to the spatial characteristics and arrangement of these related plant systems, and the requirements for clearances between systems. The complete specification of these other systems is not needed, but enough spatial information is needed to support the layout of the piping system. Users of this standard should understand the basic principles and concepts of plant and piping system design.

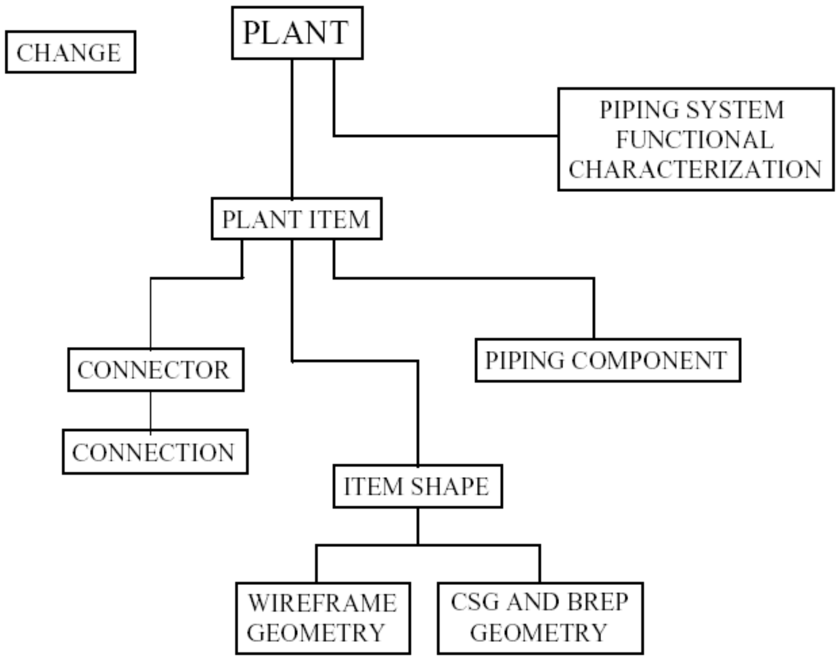


Figure 13. Extract of the Data Planning model in AP227. Top level organization of the standard

The principle focus of the AP is on piping systems and the shape and spatial arrangement of systems, including the required plant items to ensure the physical integrity of piping systems. Figure 13 contains a data planning model that provides a high level description of the requirements for this application protocol, as well as the relationships between the basic data components. The data planning model illustrates that a plant consists of *plant items* and that *plant items* may be connected to one another using connectors on the plant item. The data planning model also illustrates significant concepts found on piping and instrumentation diagrams (P&IDs): the functional view of the piping system (piping system functional characterization) and one kind of plant item: *piping components*.

The shape and spatial arrangement of plant items are represented by the item shape. The shape representation may use constructive solid geometry (CSG), solid boundary representation (B-rep) geometry, wire frame geometry, or combinations of these. The plant item shape may be represented at various levels of abstraction, from an encompassing envelope to a detailed design description. The data planning model further illustrates that the concept of change is a requirement for this application protocol. Change is applicable to each individual plant item, the relationships between plant items, and to groupings of plant items. It applies to all the concepts noted on the data.

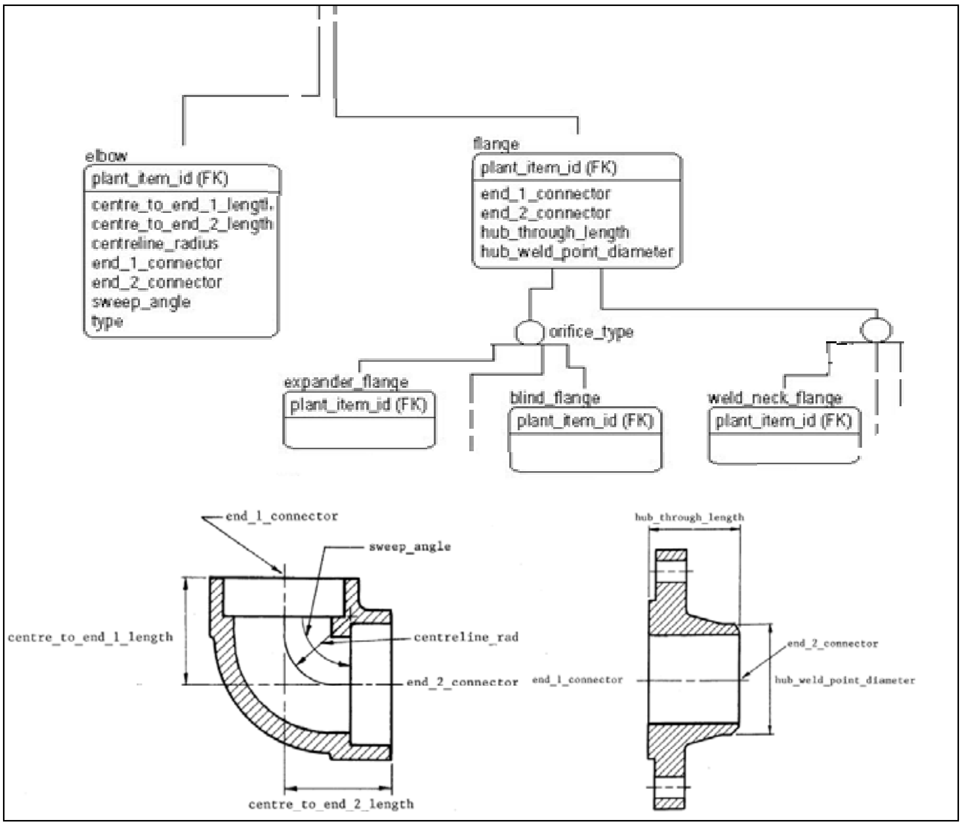


Figure 14. Part of the EXPRESS-G diagram of Flange and Elbow in Plant Design Domain - as used in MiroWalk Semantic Adaptation Module

3.5.4 An ontology based in the ISO-STEP 10303 AP-227

3.5.4.1 Ontologies in the AI Community vs. Engineering Community

As pointed out by Uschold and Jasper "*A Framework for Understanding and Classifying Ontology Applications*" ([USJ99]) in an important reference work for this research, the AI ontology community and the Engineering communities had in the past (and still have) some differences in the approach to the use and understanding of ontologies. Uschold correctly identifies that there is a need to overcome barriers created by disparate vocabularies, representations and tools in a given domain, and that the agreement on an appropriate way to conceptualize the domain and make it explicit in some language is necessary. Ironically, different communities working on ontologies (ontology research groups, software developers, standards organizations) strive to overcome the previous difficulties but in some cases the same underlying barriers apply to a common agreement between these communities.

This research shares some of the ideas of Uschold (Boeing), a world authority in the field of ontologies, regarding his opinion that a detailed engineering specification standard such as STEP is indeed a practical application of ontology, if his classification criteria for ontologies are followed. Thus, I understand in this work the term *"ontology"* in its broader sense, taking his "lowest common denominator" definition:

> *"An ontology may take a variety of forms, but necessarily it will include a vocabulary of terms, and some specification of their meaning. This includes definitions and an indication of how concepts are inter-related which collectively impose a structure on the domain and constrain the possible interpretations of terms."* [USJ99]

Quoting him further (boldface is ours):

> *This broad interpretation helps to show how both the goals and the technologies developed to achieve them are similar across the different communities. For example, common goals include reuse and interoperability. Common technologies include special purpose modeling languages (e.g., Ontolingua,* ***EXPRESS*** *and IDL) and translation tools.* ***Thus, we can easily view a number of standardization efforts (e.g., STEP, OMG) as practical applications of ontologies.*** [USJ99]

3.5.4.2 Ontology Modeling in Protégé based on ISO-STEP 10303-AP227

I have modeled the ontologies of the MiroWalk system using Protégé 2000, adapting the tags and relationships (to be more suitable for a knowledge representation model) presented in the ISO STEP-10303-227.

This serves as an important backup to the *model* part of the *semantic triangle* described before, in Figure 10. At least two modules in the overall architecture (the *Adaptive Representation Module* and the *Semantic Adaptation Module*) are directly related with the modeled ontology.

In the next section I show some excerpts of the modeled ontology, using the plug-in TGVIZ for protégé.

Table 1. Detailed example of a relevant ontology class in the piping subsystem – ISO-STEP *Valve* as used in the Mirowalk system

Class Valve

Concrete Class Extends

Piping_component

Class Documentation:

A Valve is a type of Piping_component that provides isolation or controls fluid direction or flow rate.

Template Slots			
Slot name	**Documentation**	**Type**	**Cardinality**
coating_reference	The coating_reference specifies a reference to the specification of the substances used to coat the surfaces of a Piping_system_component. For a given Piping_system_component, the value of this attribute overrides any global specification.	String	0:1
corrosion_allowance	The corrosion_allowance specifies the depth that corrosion may encroach below the surface of a piping_- system_component before action is required. For a given Piping_system_component, the value of this attribute overrides any global specification. It may be specified as a single value or as a range value. NOTE See annex L for a discussion of attributes that may be assigned a single value or a range value. The depth of the corrosion may vary over the extent of the piping_component. NOTE: or allowance is a media value between 0 and 100%	Float	0:1
heat_tracing_type	The heat_tracing_type specifies the means utilized to impart a temperature increase to the Equipment by an external wrapping or coiling. EXAMPLE Examples of heat_tracing_types include, but are not limited to, electrical or steam. ---------------- OR ALSO The heat_tracing_type specifies the means utilized to impart a temperature increase to the Piping_- system_component by an external wrapping or coiling. For a given Piping_system_component, the value of this attribute overrides any global specification. NOTE Types may include electrical or steam.	String	0:1
lining	The lining specifies a description of the substances used to line the internal surfaces of a Piping_system_- component.	String	0:1
description	The description specifies a textual explanation or summary of the Plant. The description need not be specified for a particular Plant. There may be more than one description for a Plant. ----------------------- OR ALSO The description specifies a textual explanation or summary of the Plant_item.	String	0:1
plant_item_id	The plant_item_id specifies a unique identifier for the Plant_item. Plant_item_id is required for each Plant_item.	Integer	1:1

name	The name specifies a textual label given to the Plant. ----------------------- OR ALSO The name specifies a textual label given to the Plant_item. ---------------------- OR ALSO The name specifies a textual label given to a dimension or parameter of a Plant_item_shape (see 4.2.187). EXAMPLE An example of this is the name "diameter".	String	0:1
type	The type specifies a designation that classifies the Plant_volume. or Plant_item (see 4.2.174). EXAMPLE Examples of Plant_volume object type classifications include reserved space, zone-area, area classification zone, equipment pull space, and egress for personnel. The type specifies a designation that classifies the Plant_volume. EXAMPLE Examples of Plant_volume object type classifications include reserved space, zone-area, area classification zone, equipment pull space, and egress for personnel. -------------- OR ALSO The type specifies a designation that classifies a Valve based on its purpose that defines the design of its internals and externals. EXAMPLE Examples of Valve type designations include gate, globe, check, and relief. ---------------------- OR ALSO for the Elbow fitting The type specifies a designation that classifies the Elbow. EXAMPLE Examples of elbow designations include long radius, short radius, reducing, and street. ------------------------ OR ALSO for the Structural_load_connector, The type specifies either a shear, moment, or shear and moment type of load at the connector.	String	0:1
code	The code specifies the name of the specification that the Piping_system needs to conform to.	String	0:1
plant_system_id	The plant_system_id specifies a unique identifier for the Plant_system. Plant_system_id is required for each Plant_system.	Integer	1:1
service_description	The service_description specifies a textual or summary label for the system. EXAMPLE Examples of service_description labels include Boiler Feedwater System, Paraxylene System, Pipe Rack K, and 4160V Power System.	String	0:1
definition_coordinate_system	The definition_coordinate_system is the origin and axes of the Plant that serve as the basis for the location and orientation of Plant_items (see 4.2.174) and subplants in the Plant.	String	0:1
operators	The operators specifies the name of the organization(s) responsible for the operation of the Plant. For a given plant, the operators need not be specified.	String	0:1
plant_id	The plant_id specifies a unique identifier for the Plant. Plant_id is required for each Plant.	Integer	1:1
source	The source specifies a designation that identifies a table or document that contains a list of candidate classifications that the name and description are drawn from.	String	0:1
actuator_type	The actuator_type specifies a descriptive designation of device or mechanism used to open, position, or close a Valve.	String	0:1
operation_mode	The operation_mode specifies the failure mode, as in the state of being open or closed when the actuator either has no power or is in the default position. Please note: in this implementation Open is Boolean 1 and Close is Boolean 0	Boolean	0:1

The Table 1 depicts a detailed example of one of the classes of the ontology. The current modeled ontology of the domain model has a total of:

- **298** classes
- **143** slots
- **451** frames

that represent currently the **60%** of the concepts in the ISO application protocol 227. This is enough to give a good semantic basis to most of the relevant scenarios of the walkthrough system for semantic visualization purposes. Further extensions of this implementation can cover more detailed cases but this 60% is sufficient for the different scenarios proposed in this work.

In the Figure 15 a portion (about $1/15^{th}$) of the classes of the standard that have been used in the modeling of the Domain Ontology for our application is shown, with proper adaptation of the ISO-STEP 10303 AP227 standard (see Annex I)

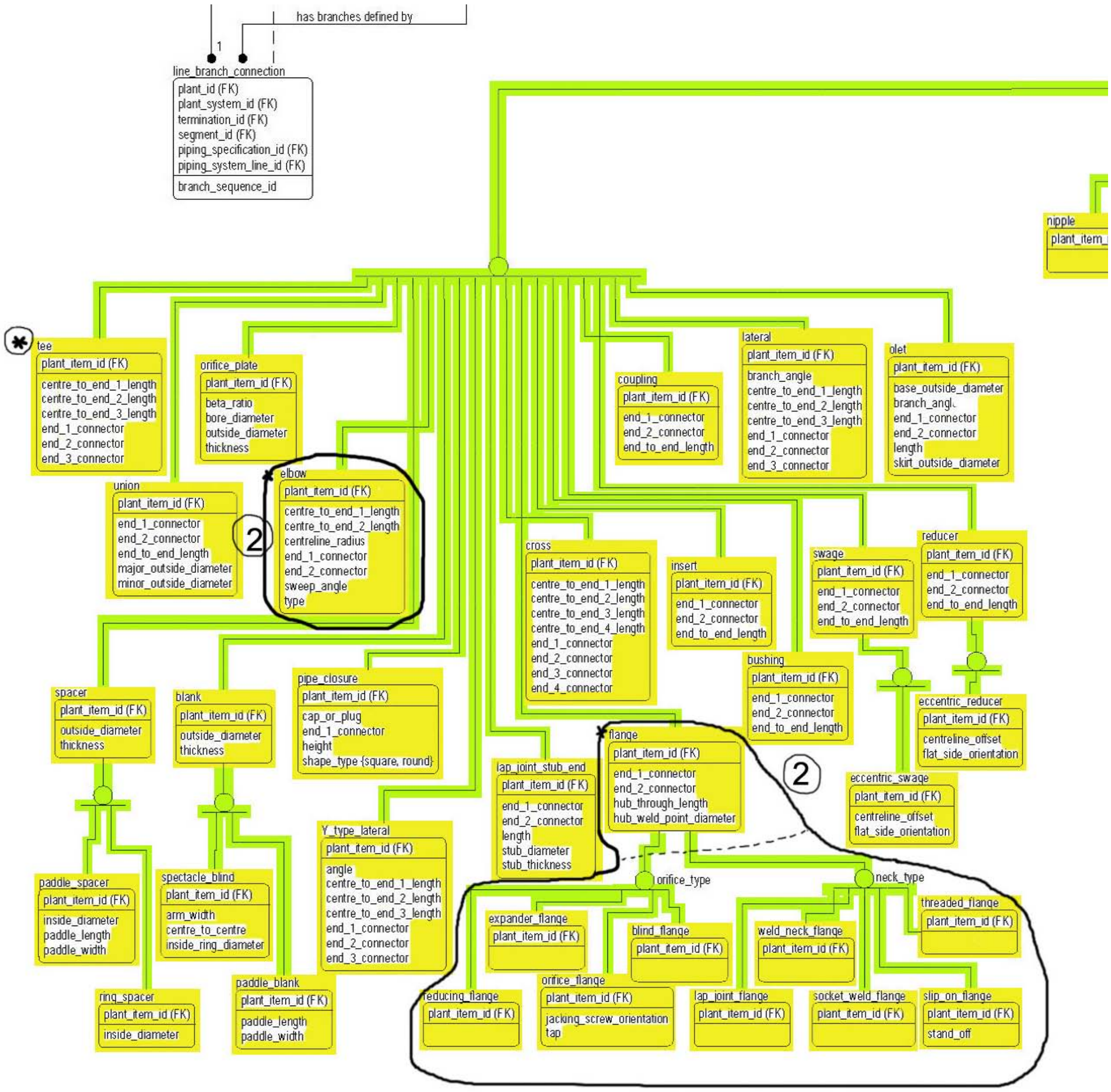


Figure 15. A partial view of ISO-STEP 10303 standard described in EXPRESS-G. Yellow boxes have their corresponding classes/slots in the ontology. The details are shown in Annex I.

For visualization and interaction purposes I have used Protégé 2000 and the TGViz plug-in, and the queries are made through a simple RDF – OWL compliant parser that interacts with the adaptive visualization module.

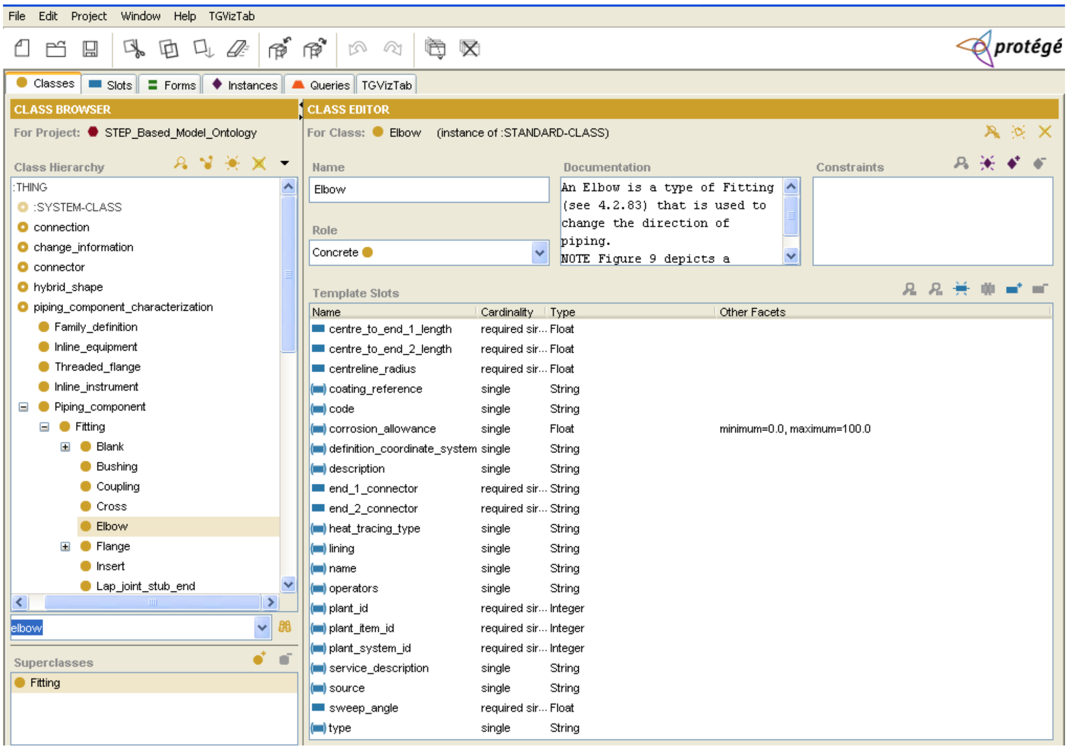


Figure 16. A screenshot of Protégé with a region of the Domain Ontology based on the AP227

In the next figures I show some of the most important regions of the ontology, visualized with the TGViz plug-in of Dr. Harith Alani (Southhampton University) [ALAN03].

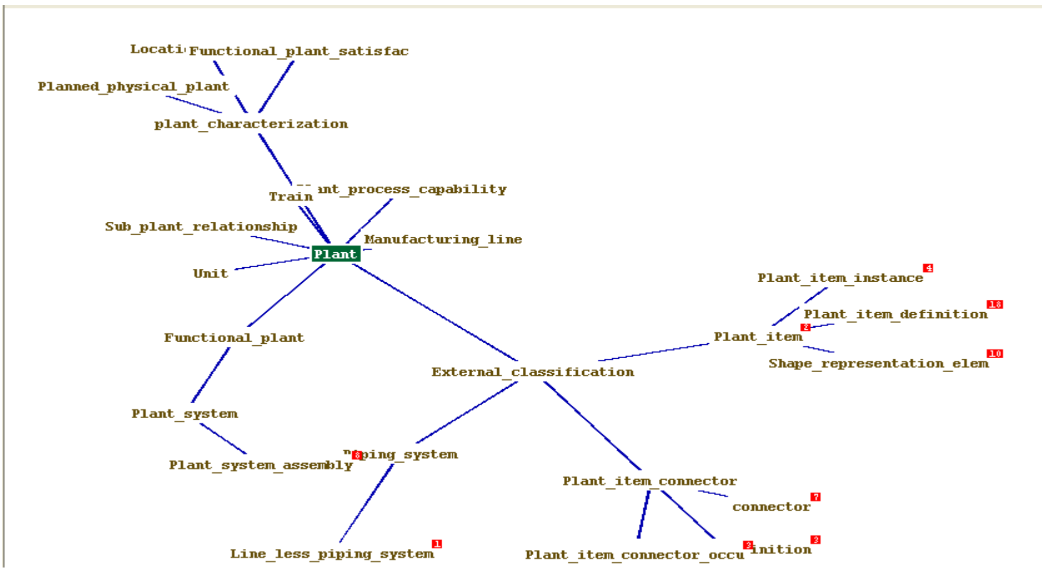


Figure 17. Industrial Plant ontology excerpt – The *Plant* root node and some important leaf nodes

Figure 17 shows a partial view of the root node of the ontology, which is the class *Plant*. As I have said in the introduction, there are several related concepts to the root concept, but those more directly related with the graphical representation of 3D CAD primitives in walkthrough scenarios are grouped around the *piping* system concept. This is due to the fact that most of the HVAC (Heating, Ventilation and Air Conditioning), as well as the piping, are responsible for most of the tessellated polygons in 3D, as well as being involved in many of the user tasks common in the domain.

It is important to recall that it is actually the *piping component* part of the ontology the one that is more relevant for the MiroWalk system, since ***it accounts for more than 40-50% of the triangles of a brute force tessellation of the 3D CAD model of almost any Industrial Plant.***

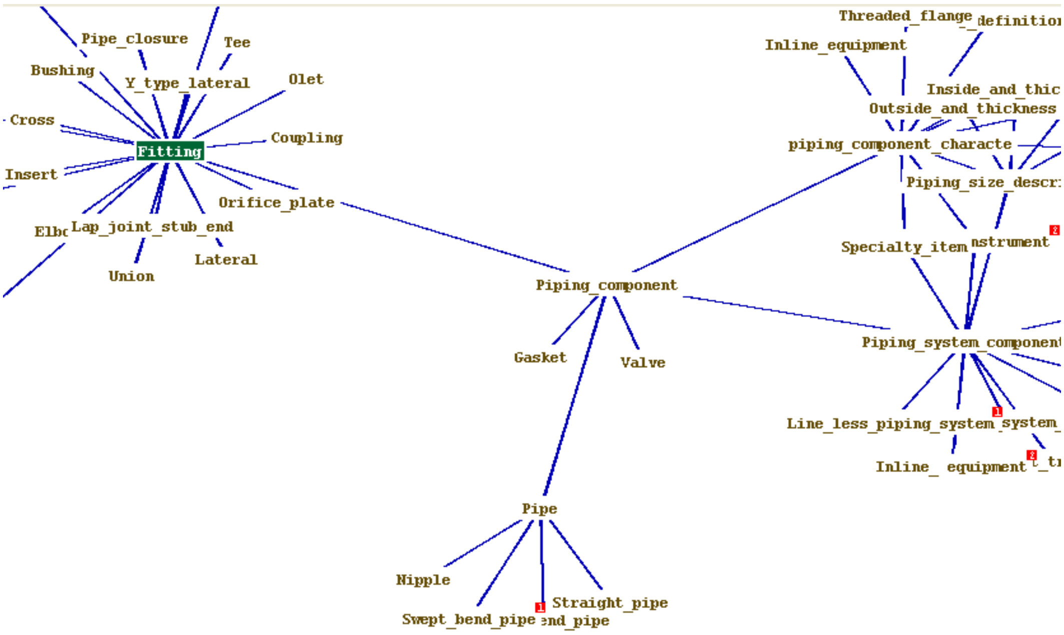


Figure 18. The *Piping Component* class – relation with *pipe* and *fitting* with Component types.

In the Figure 18 we see how different levels of the hierarchy are modeled and correspond to a high semantic relevance for each component, which is related to the 3D CAD representation of the object. Concretely, this figure shows how the component *Fitting* can be of different types (elbow, flange, etc.).

Although the 3D CAD representation is clearly different for all subclasses of *Fitting*, the core algorithms developed allow recognizing in a semiautomatic way the correct conceptual classification for all of them. Thus, it is possible to treat those *fittings* in a similar way inside the algorithms of the Mirowalk system.

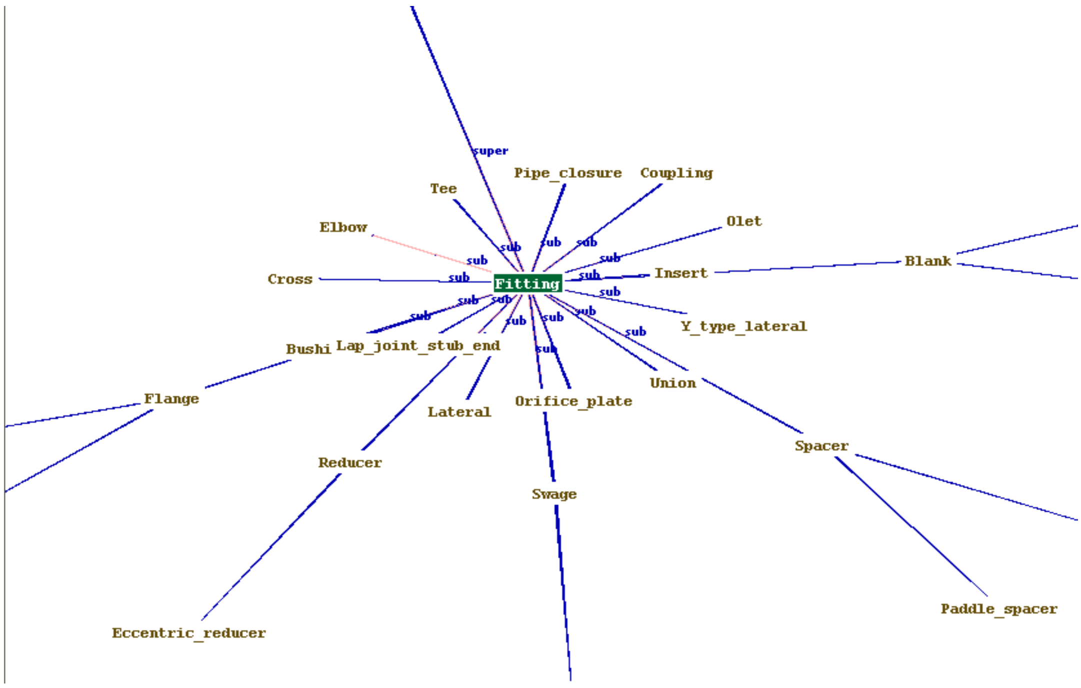


Figure 19. The *Fitting* class – Different elements are conceptually related with each other

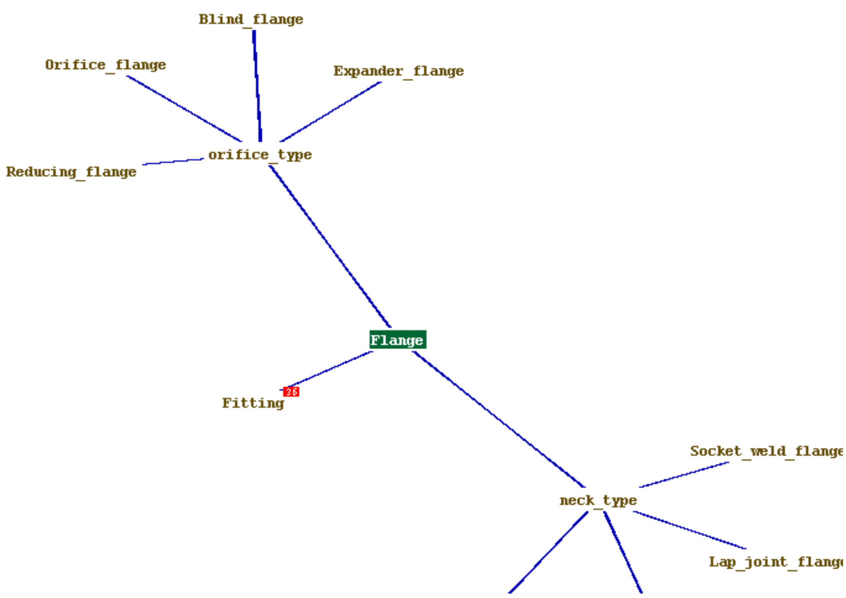


Figure 20. Some leaf nodes under *Flange* component. Flanges play an important role in the adaptation.

The other parts of the semantic triangle (user, resources) have their own ontologies to support the application of the walkthrough system. For the User part of the semantic triangle (profile/purpose), already defined in [PLS02], I have used a similar concepts implemented in the European Project WIDE (IST-2001-34417) [SSSP05b], which focused on the car design domain (See Figure 21 to see user/purpose ontologies in that project). Below, in Figure 22, a simple screenshot of the corresponding User/Purpose ontologies in MiroWalk are shown.

All the details about the specific ontologies for the system regarding User and Purpose are found in chapter 5.3, since they play an important role in the *Semantic Adaptation Module.*

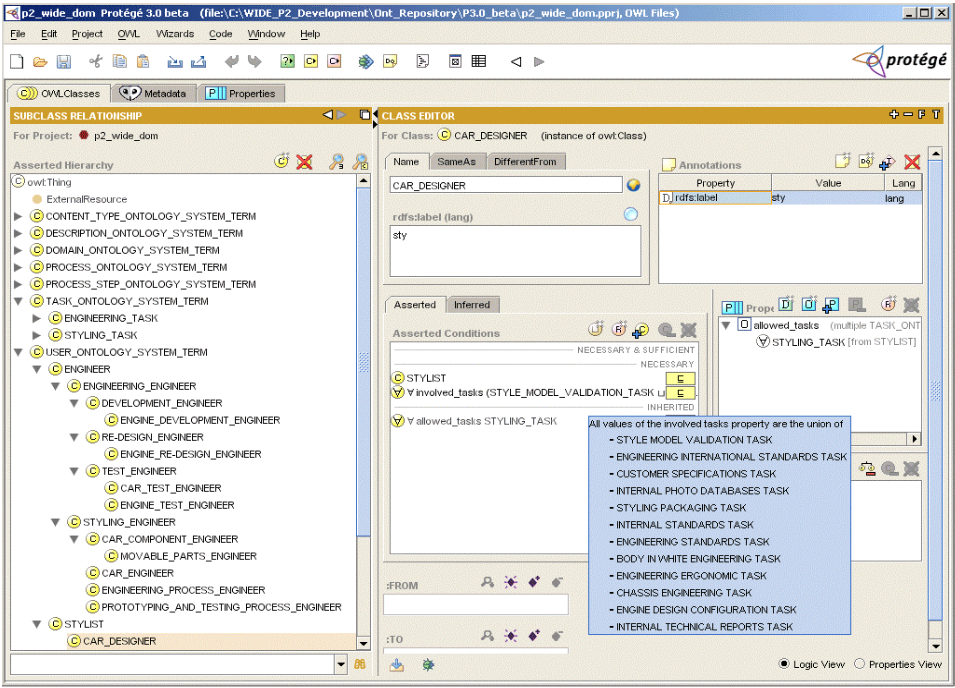


Figure 21. User and Task Ontologies model in the WIDE system (EU project IST - 2001 - 24417)

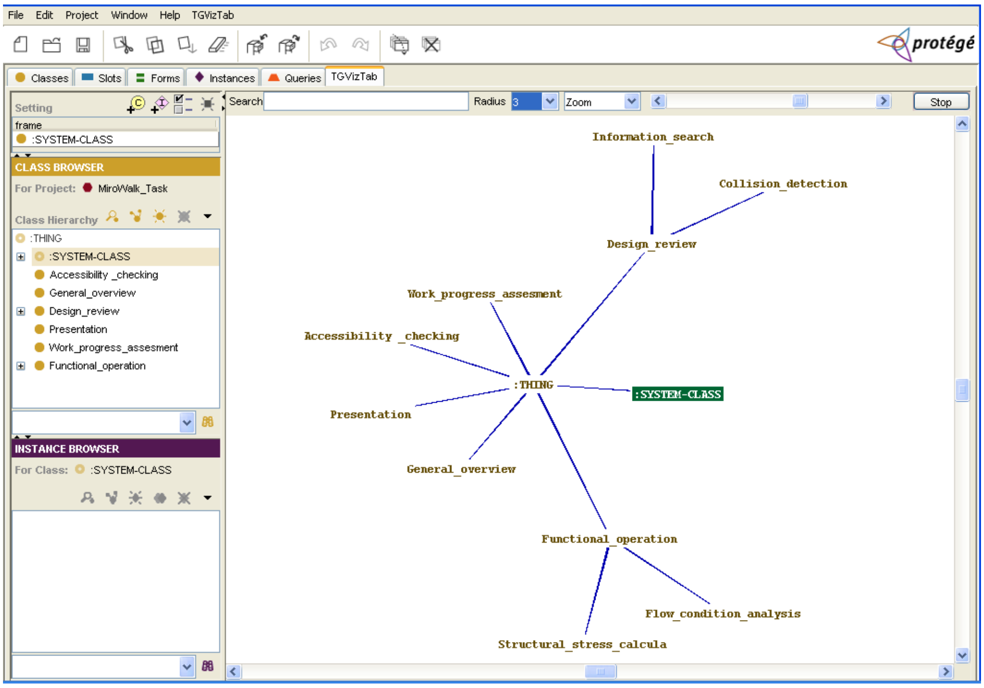


Figure 22. User and Purpose Ontologies model in the MiroWalk system – a similar approach to WIDE

3.5.4.3 Other Ontologies in the Plant Design Domain

Other approaches have been investigated in the past for ontology modeling in the Plant Design Domain. The main reference in this area is the work of Mizoguchi (Osaka University) [MKS00], whose group has investigated how an Industrial Plant Ontology can be modeled and used for functional processes (called *tasks*) such as diagnosis, monitoring and scheduling. This work was developed under the project "Development of a human interface for the next generation plant operation" in the scope of the Human Media initiative of the Japanese Government. The ontology modeling environment is called "Hozo", used for building the plant ontology and model. It is composed of graphical interface, editor and ontology/model server in a client-server architecture.

This work is essentially of complementary nature to this research in several ways: First, it focuses on operational processes, in order to have a common representation and sharing of knowledge between agents (computer or human), and not in standard physical components for visualization walkthroughs as I do. Second, it is not developed using existing standards (the ontology tools used, as well as the types of operation, components of the plant, etc. are developed by their own). This is principle an understandable decision if the goal is to investigate how a plant ontology can improve actually knowledge sharing between agents in a well constrained scenario (Oil refinery plant), and not other goals such as interoperability with other systems.

I have already initial contacts with this group in order to explore potential collaborations given the complementary nature of both approaches.

3.5.5 Conclusions of this section

I have shown in this chapter the fundamentals of the semantic approach which is central to this work, especially from the perspective of the *Semantic Triangle* Figure 10, which includes semantic considerations of the Domain, User (profile/purpose) and Resources. I have introduced a clear justification of the main approach of the proposed methodology: the inclusion of semantic aspects in a modular architecture for generation and execution of Industrial Plant walkthroughs. I have also given some indications about how ontologies are used in the methodology, and how the product lifecycle management can benefit, in general, from a semantic treatment in computer graphics applications for that domain.

In the next chapter I introduce the mathematical model for the semantic adaptation framework.

4 A MATHEMATICAL MODEL FOR THE SEMANTIC ADAPTATION FRAMEWORK

4.1 Motivation and General Considerations

In the previous chapters I have presented different issues related with the possibility to use semantic simplification for the walkthroughs of large Plant Design models. In order to complete the proposed approach, I introduce in this chapter a **mathematical model** that explicitly takes into account the semantic aspects in a general simplification framework.

This mathematical model gives **objective criteria** to decide when and how to apply semantic-steered techniques for the simplification. At the same time, it allows the evaluation and quantitative measurement of the effective influence of the semantic approach in the walkthrough generation.

Although the main purpose of the presented model is the inclusion of semantic steered techniques (especially semantic symbols) in a framework for geometry simplification, the model has also the additional advantage that is **general** enough to be applied for any kind of geometry simplification techniques, whether semantic or not.

The following questions can be solved directly or indirectly with the model:

- What is the optimal combination of traditional techniques and new semantic steered techniques for a specific combination of Resources / User/ Visualization Purpose / Model characteristics?
- How semantic aspects (such as user profile, purpose, and domain knowledge) can be mathematically related with the geometric aspects of the walkthrough model?
- When and how should specific techniques be applied to a model?
- What is the measured impact (in performance, graphical quality, functionality, etc.) of the semantic-steered simplification techniques in a Plant CAD model?
- Is it worth to apply a specific technique (e.g. semantic synonym) for a specific kind of element in a specific CAD model of a plant? When?

I present a basic model structure in a simplified form, and show how this basic model can be extended refining the underlying assumptions and simplifications for specific circumstances. In chapter 6 I present also the results of applying this mathematical model to the different examples of Industrial Plant CAD models.

4.2 Basic Definitions

Let

P be a 3D CAD model of an Industrial Plant, modelled in a specific 3D CAD system.

c_i be a *cell* / Explicit group of 3D CAD *geometric elements* representing a meaningful unit in Plant Design domain. It can be of 1 or more elements

Examples of *cells* are:

- One cylinder representing a straight section of a **pipe.**
- A group of cones, cylinders, polygons, torus, representing a **valve.**
- A group of NURBS representing a **HVAC element.**

e_{ij} be a *geometric element* in the 3D CAD system that is part of a *cell* c_i. The kinds of *geometric elements* vary between 3D CAD systems (e.g. polygon, NURBS, cylinder, torus, cone, trimmed surface, etc. etc.)

For practical purposes, the relationship between c_i and e_i can be simplified (ignoring internal relationships and dependencies between elements) as:

$c_i = \{e_{i1,} e_{i2,\ldots,} e_{ij}\}$ For a cell i with j elements.

Let also

$C = \{ x \mid x \text{ is a } cell\ c_i \}$ be the set of all *cells* in a 3D CAD model of an Industrial Plant.

expressed differently,

$$C = \{ c_1, c_2, \dots , c_n \}$$

For the mathematical model, the simplified definition of the plant P is:

$$P = C = \{ x \mid x \text{ is a } cell\ c_i \}$$

Note that this is only an adequate **simplification** for the mathematical model; a 3D CAD model of a plant is much more than just the set of its groups of elements. Hierarchical relationships, parametric dependencies, relation with PDM and non-geometric information, etc. are also integral part of the 3D CAD model of the plant.

4.2.1 ISO-STEP 10303-AP227 standard categories

Let

ct_i be an ISO-STEP 10303-227 Plant Item category.

For instance, I could assign, according with the standard, j categories in an arbitrary order.

ct_0 = ***FLANGE*** (STEP COD. 4.2.84)

ct_1 = ***ELBOW*** (STEP COD. 4.2.66)

ct_2 = ***STRAIGHT PIPE*** (STEP COD. 4.2.232)

…

ct_j = ***VALVE*** (STEP COD. 4.2.264)

and

$$CT = \{ x \mid x \text{ is an ISO-STEP Plant Item Category} \}$$

be the set of all ISO-STEP Plant Item Categories. This is the same as:

$$CT = \{ ct_0,\ ct_1,\ ct_2,\ \dots,\ ct_j \}$$

4.3 Mathematical Definition of the System Architecture Modules

Let's introduce at this point the architecture of the methodology proposed in this work. A more detailed explanation of the proposed architecture, the description of each module, and the implementation strategies related, can be found in Chapter 0.

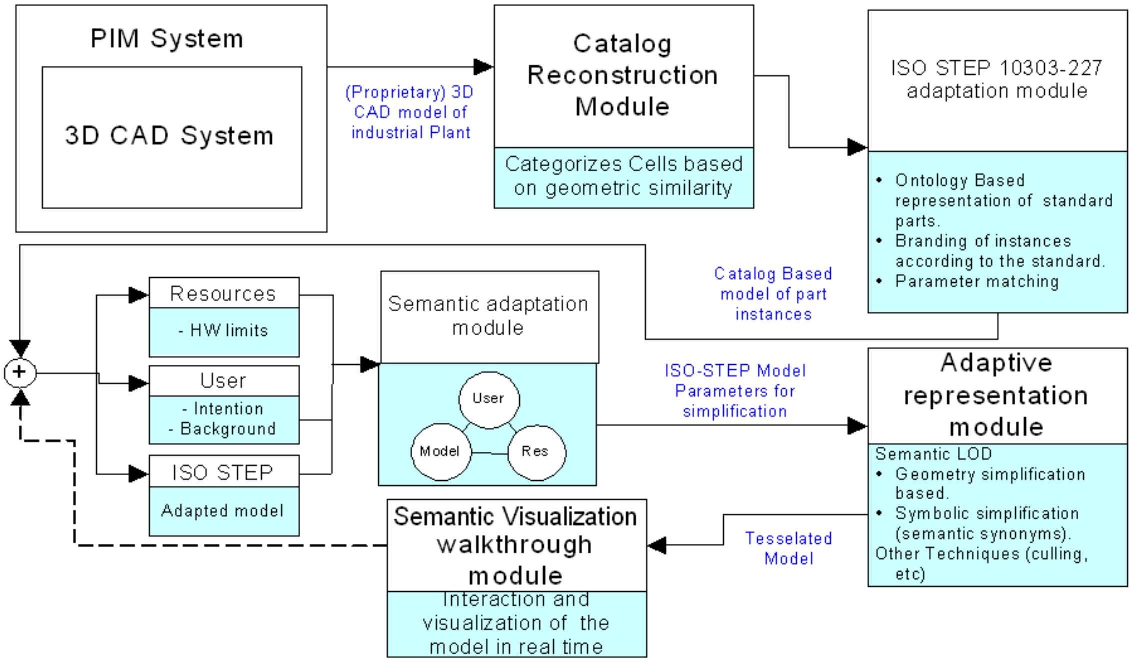


Figure 23. An Architecture for the Semantic Visualization of Industrial Plant Models – Modules view

Thus, to make a very simplified description, the *Catalog Reconstruction Module* introduces the *spatial instancing* explicitly, for those cases in which the 3D CAD model does not hold this information (which is a common situation).

The *ISO-STEP 10303-AP227 Adaptation Module* classifies the instances in the model into categories corresponding to the STEP standard of Industrial Plant Design. The *Semantic Adaptation Module* takes into account the adapted model as well as the available resources, the user profile and the visualization walkthrough purpose, and applies the *semantic triangle* criteria (Figure 10) to generate parameters to select appropriate techniques for rendering.

The *Adaptive Representation Module* selects and applies the best tessellation and rendering techniques to use during the visualization walkthrough, based on the criteria and parameters of the previous module.

Finally, the *Semantic Visualization Walkthrough Module* is in charge of producing for the user the interactive walkthrough of the adapted model using the available resources, and considering the domain and purpose involved.

4.3.1 The Catalog Reconstruction Module

In the system architecture (Chapter 5.1) it is explained that the task of the *Catalog Reconstruction Module* is to categorizes *cells* based on geometric similarity. From the definitions given below, a summarized and redefined formulation of this module is given:

The goals of the Catalog Reconstruction module are:

(i) *To identify a suitable equivalence relation* $\mathfrak{R}_{\mathrm{cm}}$ *between cells in a plant model according to the cell matching definition* (see definition in chapter 5.1.5)

(ii) *to find an algorithm to implement computationally* $\mathfrak{R}_{\mathrm{cm}}$ *in an efficient way*

(iii) *to execute that algorithm on a specific plant model* P

(iv) *to find the quotient set of* $C\,/\,\mathfrak{R}_{\mathrm{cm}}$ *for that plant model* P

(v) *to find the equivalence classes* $G_{\mathrm{a}}, G_{\mathrm{b}}, \ldots, G_{\mathrm{z}}$

given the restrictions of available information and ordering of the inner structure of the implemented cells in a specific 3D CAD model and CAD system.

Notice that this goal is completely independent from the specific domain, and is related only with the geometric representation of the *cells*. Also, notice that it is independent of the specific *algorithm* implemented to realize $\mathfrak{R}_{\mathrm{cm}}$ .Thus, this module is also directly applicable to other domains where 3D CAD models are generated, making the overall approach more general and extensible.

4.3.2 Classes of equivalence for Geometric Similarity Equivalence Classes

We define a *partition of a set o*n C based on ***Geometric Similarity Equivalence Classes*** G_j, which depend only on explicit geometric characteristics of the *cells*.

First, in Chapter 5.1 (Catalog Reconstruction Module) a detailed exposition of the the *cell matching* problem is introduced, which is one of the key aspects of that module, as well as specific algorithms to solve it. From Chapter 5.1.5 (Catalog Reconstruction Module), the *cell matching problem* can be stated as follows:

> *Given two cells C_i and C_j, each composed by an unordered set of geometric primitives, C_j matches or is an instance of C_i if a **rigid body transformation matrix** T exists that transforms C_j into C_i .*

It is well known in Computer Graphics fundamentals that a "rigid body" transformation matrix [VAND04] preserves the *lengths and angles* of the original geometry. Evidently, rotation and translation matrices are rigid body transformation matrices, as well as matrices resulting from a composition of rotation and translation matrices. The geometric meaning of applying a rigid body transformation matrix to a 3D object is to change its position and/or orientation, preserving its geometry (lengths/angles).

In our approach, we assign the `rigid body transformation matrix` T to be the condition for the requested $\mathfrak{R}_{cm}$:

$$c_i \; \mathfrak{R}_{cm} \; c_k \qquad \text{if } \exists\, T_{ik} \text{ such that } \quad T_{ik} \cdot c_i = c_k$$

Notice that also other definitions of $\mathfrak{R}_{cm}$ could be possible, I have assigned this one as the most convenient for the proposed methodology.

It is easy to show that $\mathfrak{R}_{cm}$ is indeed an *equivalence relation* in C (as defined in [MAR92]) since:

- $\mathfrak{R}_{cm}$ is a *binary relation defined in* C
- $\mathfrak{R}_{cm}$ is *reflexive*
  - Proof: If we let $T_{ii} = \mathbf{I}$ (*identity matrix*):

    $\forall\, c_i \in C: \quad c_i \,\mathfrak{R}_{cm}\, c_i$
- $\mathfrak{R}_{cm}$ is *symmetric:*
  - Proof: T_{ik} is a *rigid transformation* $\Rightarrow$ T^{-1}_{ik} exists, and

    $T_{ki} = T^{-1}_{ik} \qquad T_{ki} \cdot c_k = c_i$

    Therefore $c_i \,\mathfrak{R}_{cm}\, c_k \Rightarrow c_k \,\mathfrak{R}_{cm}\, c_i$
- $\mathfrak{R}_{cm}$ is *transitive*

- Proof: Let $[c_i \,\mathfrak{R}_{cm}\, c_k, c_k \,\mathfrak{R}_{cm}\, c_m]$

  If we let $T_{im} = T_{ik} T_{km}$, $T_{im} \cdot c_i = c_m$

  T_{im} exists and therefore $c_i \,\mathfrak{R}_{cm}\, c_m$

We write as usual that a and b are *equivalent* on the *equivalent relation* $\mathfrak{R}_{cm}$ in this form:

$a \cong b \pmod{\mathfrak{R}_{cm}}$	in a rigorous manner, or just
$a \sim b$	since we know the equivalence is on $\mathfrak{R}_{cm}$

Now that we have shown that the ***cell matching*** **relation is indeed an *equivalence relation*** in C, we can use it to determine ***partition*** **on C in *equivalence classes*** G_j as follows:

Let $a, b, c, \ldots, y, z \in C$

G_a	the	*equivalence class*	of all $c_i \sim a$
G_b with $b \notin G_a$	the	*equivalence class*	of all $c_i \sim b$
G_c with $c \notin G_a, c \notin G_b$	the	*equivalence class*	of all $c_i \sim c$
…			
G_z with $z \notin G_a,\ c \notin G_b, \ldots, c \notin G_y$	the	*equivalence class*	of all $c_i \sim z$

Note that by definition of a *set partition*,

$$\forall\, c_i \quad \exists\, G_{j \neq k} \Rightarrow c_i \in G_j \text{ and } c_i \notin G_k$$

Thus,

$$C = G_a \cup G_b \cup G_c \ldots \cup G_y \cup G_z$$

And the *quotient set* of C by R is

$$C/\mathfrak{R}_{cm} = \{ G_a, G_b, G_c, \ldots, G_y, G_z \}$$

In Figure 24 a schematic representation of $\mathfrak{R}_{cm}$ and the quotient set $C/\mathfrak{R}_{cm}$ is shown. Notice that, as explained in detail in the chapter 5.1 (the *Catalog Reconstruction* module), each equivalence class G_i parts can have different inner order, position and orientation. Note also that different equivalence classes are generated for objects that are actually of the same kind, but are composed either by different primitives or modelled in different ways.

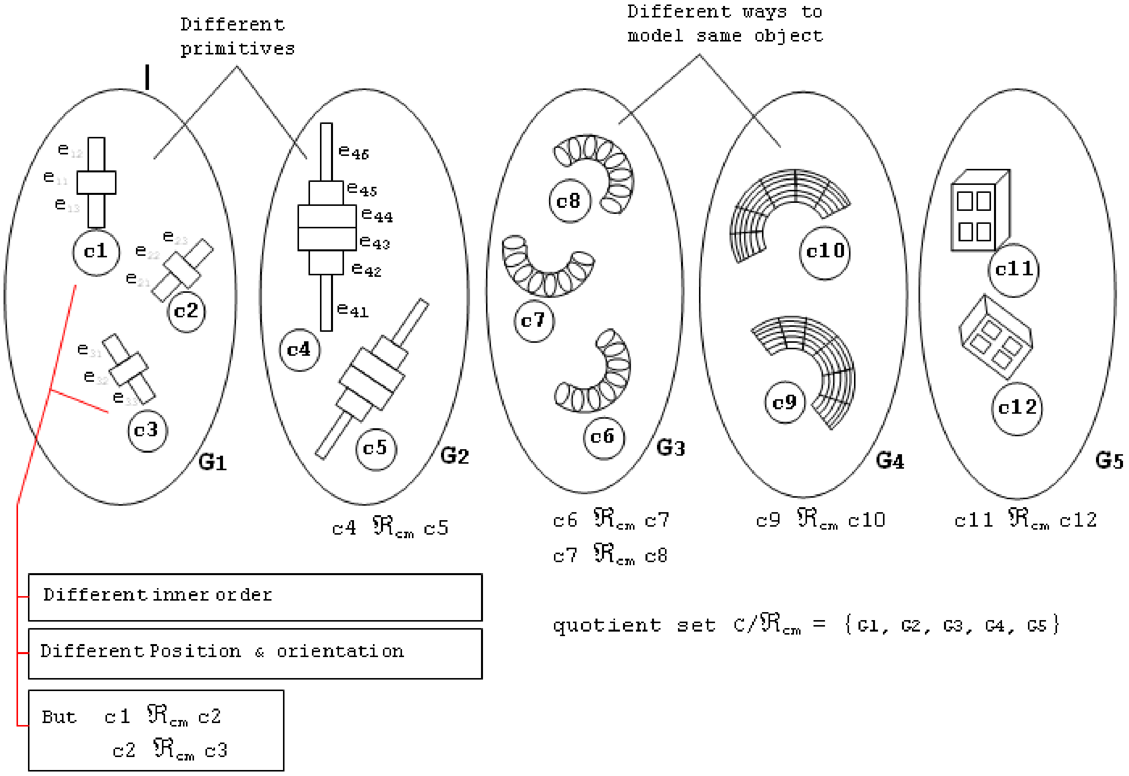


Figure 24. Schematic representation of the equivalence relation $\mathfrak{R}_{cm}$ and the quotient set $C/\mathfrak{R}_{cm}$

4.4 The ISO-STEP 10303-227 Adaptation Module

This module (ISO-STEP Adaptation module) must find a way to associate the grouping structures (*equivalence classes*) coming from the Catalog Reconstruction Module to the domain of Plant Design (*categories in STEP*), in order to increase the explicit semantics associated of the geometric groups, and therefore, to be able to apply semantically steered techniques for model simplification. Below we present this as a mathematical model.

From the previous module (catalog reconstruction) we obtain the *equivalence classes* G_a, G_b, … , G_z and the *quotient set* $C\,/\mathfrak{R}_{cm}$. Shortly, the purpose of the *STEP Adaptation Module* is to get a relation between the *equivalence classes* (of pure geometric nature) and the *categories of Plant Design elements* in the ISO-STEP 10303-227 standard (of semantic value in that domain). In this way, other modules in the system architecture can apply semantically steered techniques for model simplification optimized for that domain. This is not possible in a purely geometric approach.

We can redefine mathematically the purpose of this module as follows:

The main goals of the STEP-13013-227 Adaptation Module are:

(i) *to find a* **binary relation** $\mathfrak{R}_{am}$ *that associates* $C/\mathfrak{R}_{cm}$ *and* CT *according with the domain semantics of the equivalence classes* G_a, G_b, G_c, … , G_z.

(ii) *to classify the equivalence classes* G_a, G_b, … , G_z *and the underlying cells* c_i *in a specific plant model* P *according to* $\mathfrak{R}_{am}$, *it is, to associate each of them to a category in* CT *(when possible, it is, when* i, j *exists such that* $G_i\ \mathfrak{R}\ ct_j$*). The results of this classification is the* classifiable set S.

(iii) *To find the equivalence classes* G_a, G_b, … , G_z *and the underlying cells* c_i *that* <u>can not</u> *be classifiable in* CT, *this is, that no* i, j *exists* *such that* G_i $\mathfrak{R}$ ct_j. *The result of this classification is the* non classifiable set $\overline{S}$.

Now we discuss in more detail how this mathematical definition is applied.

Mathematical meaning of $\mathfrak{R}_{am}$

Let's recall that the *quotient set* $C/\mathfrak{R}_{cm}$ is formed by all the *equivalence classes* G_a, G_b, G_c, … , G_z. The meaning of such classes is that each of them contain *cells* that share an *equivalence relation*, which in this case is $\mathfrak{R}_{cm}$: if the cells *match* each other geometrically.

The ***binary relation*** $\mathfrak{R}_{am}$ associates each of these *equivalence classes* of $C/\mathfrak{R}_{cm}$ to one category in the ISO-STEP norm, ct_i. The *property* to verify in the binary relation is:

> $\mathfrak{R}_{am}$ relates one *equivalence class* G_i *of* $C/\mathfrak{R}_{cm}$ to *one and only one* category ct_j *of* CT, *if the geometric representation of any cell in* G_i *can be interpreted by a domain expert as a valid representation of an instance of the abstract category* ct_j.

In Figure 25 a schematic representation of $\mathfrak{R}_{am}$ is presented.

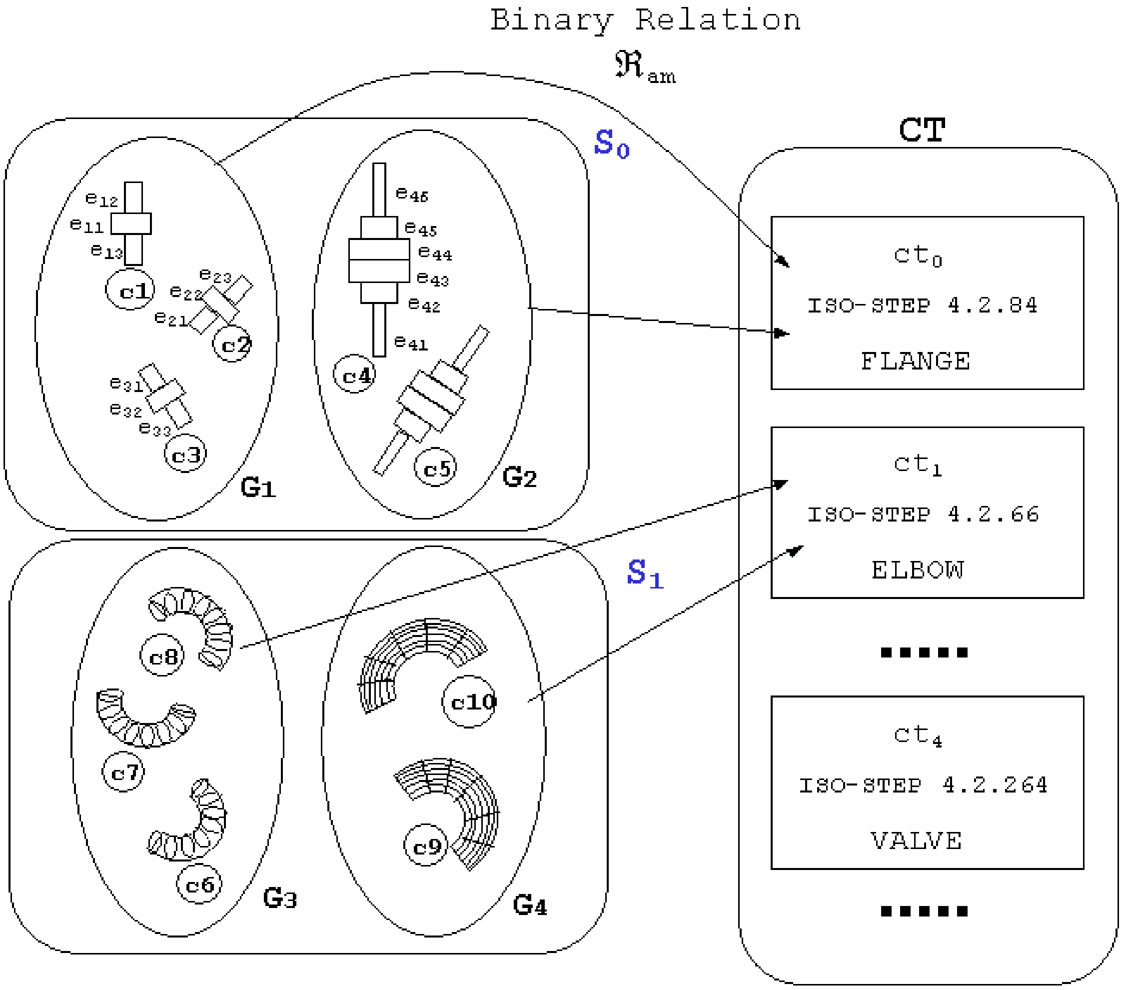


Figure 25. A Schematic representation of the binary relation $\mathfrak{R}_{am}$ between G_i and ct_j

Note that this relation has the following properties:

- $\mathfrak{R}_{am}$ is <u>not</u> an *equivalence relation*, since it is not defined in a single set, but between two different sets ($C/\mathfrak{R}_{cm}$ and CT)
- $\mathfrak{R}_{am}$ is <u>not</u> a *function* since it is <u>not every element</u> in $C/\mathfrak{R}_{cm}$ can be associated to an element in CT.
- By definition of a *binary relation,* $G_i\ \mathfrak{R}_{am}\ ct_j$ means that the property defining the relation $\mathfrak{R}_{am}$ applies for i,j, but it's also possible that there exist a G_k such that no ct_j can be related to G_k. (This is, it is possible that a geometric representation of a *cell* can not be associated by an expert to a category in the domain according to the ISO-STEP standard).

4.5 ISO-STEP 10303-227 Classifiable Set

For a specific plant P, with a set of cells C, we define a subset $S \subset C$, called *classifiable set:*

$$S \quad = \{x \mid x \in C \text{ and } x \text{ can be associated to one category in } CT\}$$

This is, each *cell* in S corresponds to a category in CT.

We will show that S is actually composed by a *set partition* according to this mathematical sense in Set Theory. Let us define:

$$S_0 \quad = \{x \mid \exists\, G_i :\ x \in G_i \wedge \text{and } G_\mathrm{i}\ \Re_{\mathrm{am}}\ ct_0\}$$

$$S_1 \quad = \{x \mid \exists\, G_i :\ x \in G_i \wedge \text{and } G_\mathrm{i}\ \Re_{\mathrm{am}}\ ct_1\}$$

$$S_2 \quad = \{x \mid \exists\, G_i :\ x \in G_i \wedge \text{and } G_\mathrm{i}\ \Re_{\mathrm{am}}\ ct_2\}$$

…

$$S_j \quad = \{x \mid \exists\, G_i :\ x \in G_i \wedge \text{and } G_\mathrm{i}\ \Re_{\mathrm{am}}\ ct_\mathrm{j}\}$$

But, since the STEP categories are disjoint:

$$S \quad = \bigcup S_\mathrm{i}\ \ (S_\mathrm{h} \cap S_\mathrm{k} = \varnothing \quad \text{if} \quad h \neq k)$$

Therefore it is a valid set partition, and this is the same as:

$$S_0 \ = \ \{c \in S \mid c \text{ can be associated as an element of category } ct_0\}$$

$$S_1 \ = \ \{c \in S \mid c \text{ can be associated as an element of category } ct_1\}$$

$$S_2 \ = \ \{c \in S \mid c \text{ can be associated as an element of category } ct_2\}$$

…

$$S_j \ = \ \{c \in S \mid c \text{ can be associated as an element of category } ct_j\}$$

We can also find easily the *non-classifiable set:*

$$\overline{S} \quad = C - S$$

which is the set of all *cells* that can <u>not</u> be associated to a category in CT.

Figure 26 shows the relationship between the classifiable set and the non-classifiable set.

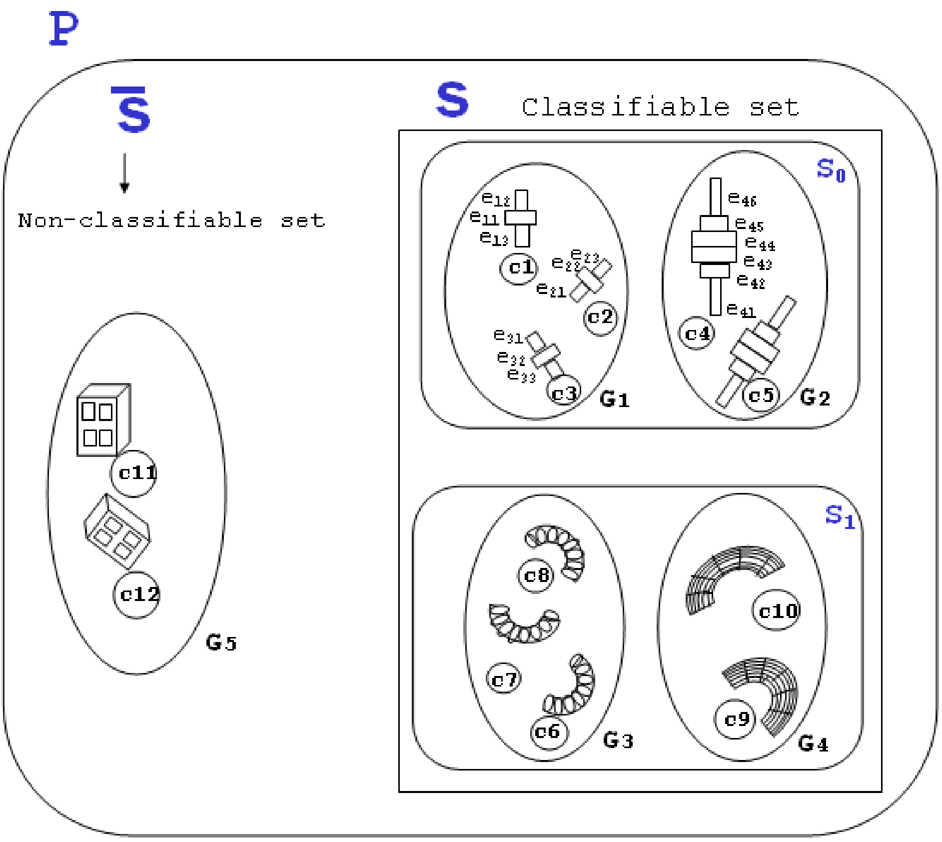


Figure 26. Scematic representation of the classifiable set S and the non-classifiable set $\overline{S}$

Notice also that having the classifiable set S we can define a *function* of S in CT, since all *cells* in S have an image in CT:

$$f(c_s) \quad = \quad ct$$

Thus, the mathematical description of the module is complete.

Notice that the **most important aspect** of this module is to find a suitable algorithm that implements the classification according to the relation $\mathfrak{R}_{am}$ (and indirectly, the implementation of $f(c_s) = ct$.

This is not an easy task, and is basically what is now possible in the Mirowalk system with the help of semantic technologies modelling and semiautomatic classification as described in chapter 0 and in [PTWS05c] and [PWTS04a].

4.6 The Cell Concentration concept : q_i / p

In this section we will introduce the concept of *Cell Concentration*. Aided by this concept and the definitions above, we will formulate later a semantic optimization problem of general nature for 3D CAD models in a specific domain, independent from the size of the model and the actual subsection rendered after culling.

In chemistry, *concentration* is the relative proportion of a substance in a solution or mixture. In an analogue manner we define the *cell concentration of type i for a plant section* as the relative proportion of cells of a specific type with respect to the total number of cells of that section.

Let:

P be the 3D CAD model of an Industrial Plant (see 4.2)

p be the number of cells in P (also P *cardinality*)

q_i be the number of cells belonging to the *class partition* S_i (see Table 4)

PS be a *section (subset)* of a plant P ($PS \subset P$)

ps be the number of cells in PS (also PS *cardinality*)

qs_i be the number of cells belonging to both S_i and PS.

q_i/p *is the cell concentration of class* i *for a Plant* P

qs_i/ps *is the cell concentration of class* i *for a Plant Section* PS

We present some postulates related to the *cell concentration* **q_i/p** are:

<u>Postulate 1.</u> For the specific domain of Plant Design (and other similar domains with well constrained basic cells) $\Sigma\, q_i /p \approx 1.0$

In fact, $\Sigma\, q_i /p$ is an indirect measure of (i) the efficiency of the catalog reconstruction and standard adaptation modules, and (ii) the adjustment of the model to the expected characteristics of the domain. Although in basically all 3D CAD models of Plant Design it is expected to find non classifiable cells according to the domain, a high proportion of the cells should belong to some S_i.

<u>Lemma 1.1.</u> If $\Sigma\, q_i / p << 0.5$ *either* $\Re_{am}$ *is not well defined, or* $f(c_s) = ct$ *is not well implemented, or the reference standard is not complete, or the model is atypical for the domain.*

This lemma is highly useful, since it helps to identify in an early stage of the semantic simplification if the necessary conditions from the model semantics perspective exist or not.

<u>Lemma 1.2.</u> $\Sigma\, q_i / p$ *increases proportionally with the number of implemented categories in the ISO-STEP Adaptation module.*

This is an interesting fact to consider in ongoing implementations of the module, since it as a direct effect on the semantic simplification: it depends on the covered categories in the standard. However, the focus should be to assign priorities of implementation to those S_i that produce the highest number of triangles.

<u>Postulate 2.</u> The values of all q_i / p *tend to have similar values, within some limits, between different 3D CAD models of the same domain (in this case Plant Design), independently from the modeller used or the size of the model.*

This is the consequence of two facts. First, all 3D CAD models in Plant Design share more or less the same kind of cells from a semantic perspective (but *not* from a geometric perspective!). This is indeed the basic idea behind the creation of a standard such as STEP ISO13013-AP227. Second, between models of complete plants (independently from the size/complexity or modeller used) it is true that the proportion between the different basic components is relatively similar: e.g. the number of valves is somehow proportional to the number of pipes, and so on. Empirical measures between the models studied have corroborated this fact. From this, it can be deduced that q_i / p have similar values between different 3D CAD models of Plant Design.

<u>Postulate 3.</u> If PS *is a spatial subsection of a complete plant* P*, then* qs_i / ps *has the general tendency to be similar to* q_i / p *(this is:* $qs_i / ps \cong q_i / p$ *)*

This postulate expresses that a subset of a complete plant has basically a very similar *cell concentration* than the whole plant. This is however only true if

(i) it is a *spatial subsection:* this is, if the subsection is composed by *all* cells constrained between given spatial limits. Note that this is *not* true for a functional subsection or attribute subsection (e.g. only pipes, only green cells, …).

(ii) if the subsection is big enough to be representative for the whole plant (only a few cells are not representative).

Notice that this is somehow similar to the concept of *uniform density* in chemistry too: we are saying indirectly that the relative proportion of cells hold for the whole and for the part. However, in any case, it should be clearly stated that this is just a *general tendency* and that there may be spatial subsections in a model with different values for the *cell concentration* (as for instance a specialised room with only ventilation equipment).

<u>Postulate 4.</u> *q_i / p and qs_i / ps can be directly calculated very fast, or predicted with relative confidence according to previously calculated cell concentrations in other models.*

The calculation of *cell concentrations*, either for complete plants or for spatial subsections, is very easy since it is just the relation of a couple of counting operations. On the other hand, in some cases it might be useful to just *predict* the value of the cell concentrations for efficiency reasons, or to have approximate predefined values for some variables in the mathematical model. For the latter case, it is clear from Postulate 2 that precalculated values for some 3D CAD models are a good basis for prediction of new models.

4.7 The Functional Semantic Factor $fsem$ and the Geometric Aesthetic Factor $fges$

We define two important concepts that will be used in the mathematical formulation:

the *Functional Semantic Factor* $fsem$ and

the *Geometric Aesthetic Factor* $fges$.

These two factors weight the influence of a special technique and/or cell has on the walkthrough experience taking into account semantic and functional factors.

4.8 The Functional Semantic Factor *fsem*

This factor (with values between 0.0 and 1.0) has a numeric value used to quantify the *relative influence of graphical representation of a cell with regard to functional and semantic considerations* for a cell. Albeit the concrete value of *fsem* is somehow of subjective nature, it is very helpful to have this factor in numerical form, especially for its further mathematical treatment. Basically, this allows the *weighting* of the different techniques applied with regard to functional and semantic considerations.

> *The value of fsem quantifies the subjective effectiveness of the 3D graphical representation of a cell $c_i \in S_i$ in a walkthrough to convey the* ***functional and semantic role of that representation for a specific user purpose and profile*** (0.0 is lowest, 1.0 is highest).

The *functional and semantic role* in the definition above relates exclusively with the ability the 3D representation to express the meaningful aspects of a cell with regard to its role for a specific *user purpose and profile.* As this 3D representation is a direct effect of the selected *technique* used to generate the tessellation of the cell, it is clear that:

$$fsem = f(\text{user purpose, user profile, technique used, } c_i \in S_i)$$

The Table 3 illustrates with some examples how the user purpose, user profile and technique used affect the value of *fsem*. Of course, the highest *fsem* values are better for the walkthrough purposes, when possible. The comments in the table explain some of the considerations related with *fsem*.

Notice that *fsem* has <u>no</u> considerations related to

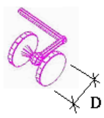
- Aesthetic aspects
- Tessellation size (number of triangles)

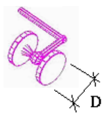
These important aspects are considered in other factors, later on (especially *fest*).

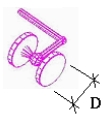
Now, some comments about the examples in the table. First, the *brute force tessellation* technique seems to be the best technique for *fsem*. This corresponds to the intuitive idea that the user (any user) would prefer a very detailed representation since it conveys the most of the semantic / functional aspects. However, it must be noticed that other aspects, especially the cost in number of triangles, not always allow this representation. A schema for optimal management of the resources, user purpose/ profile and model characteristics would probably choose a different technique when suitable, in order to decrease the number of triangles generated. Second, the Geometric LOD representation seems very similar in $fsem$ values to the *Semantic Symbol* technique. This is indeed true, but with an important difference:

> *Although the $fsem$ values of Geometric LOD and Semantic Symbols are similar, other factors (number of triangles and resources needed) are much smaller in the Semantic Symbols.*

Table 2. Example of variability of *fsem* values for the same cell with different user profiles, purposes and techniques.

	Technique	*fsem*	Comment
Valve  User Profile: **Manager** User Purpose: **General Overview**	Brute force tessellation	**1.0**	The detailed representation obtained with a brute force tessellation (with small geometric tolerance) would produce a highly detailed representation, that for a *Manager* in a *General Overview* purpose would convey all semantic and functional aspects he expects.
	Geometric LOD e.g. 1/2 the triangles of brute force	**1.0**	Although the "graphical quality" decreases, for the purpose of a general overview, by a manager, it has no noticeable effect in functional and semantic role, therefore *fsem* is also 1.0.
	Drop Culling (replacing with pipe section)	**0.6**	This technique has a more important effect on functional / semantic role. Although the purpose is *General Overview* and therefore the details are not so important, just to "ignore" the valves will be a noticeable change (although tolerable).
	Valve Semantic Symbol	**0.7**	The *semantic symbol* technique may appear somehow strange to a manager who is not familiar with symbolic representations (as an engineer is), with a small risk that the semantics related with the valve are not well understood. However, it has a high *fsem.*

	Technique	*fsem*	Comment
Valve  User profile: **Piping Engineer** Purpose: **Design Review**	Brute force tessellation	**1.0**	The most detailed representation also conveys the highest functional / semantic characteristics. The drawback is clearly the high cost.
	Geom LOD (½)	**1.0**	Also conveys a high semantic / functional sense. However the aesthetic/acceptance may suffer, but this is independent from *fsem*.
	Drop Culling	**0.0**	This technique has the lowest *fsem* not for this profile / purpose, since the semantics are completely lost and are highly relevant in this context.
	Valve Semantic Symbol	**0.9**	An engineer is more used to work with symbols, and therefore the semantic / functional sense of the symbol would be easily understood.

	Technique	*fsem*	Comment
Valve  User profile: **Manager/ Engineer** Purpose: **Presentation to Client**	Brute force tessellation	**1.0**	The client typically wants to see a very detailed representation of all details of the plant, this technique allows it (with high cost).
	Geom LOD (½)	**0.5**	In this context the semantic / functional aspects are affected by the technique, the client would expect a better representation.
	Drop Culling	**0.0**	The lowest *fsem* not for this profile / purpose, the client would be puzzled not seeing the valves.
	Valve Semantic Symbol	**0.5**	The client would probably understand well the symbols but the semantic / functional effect might be lower than expected

	Technique	*fsem*	Comment
Valves and Pipes User profile: **Structural Engineer** Purpose: **Collision Detection**	Brute force tessellation	**0.9**	The semantic / functional aspect required (exact geometric representation) would be anyhow affected by static tessellation accuracy.
	Geom LOD (½)	**0.4**	The semantic / functional aspects are heavily impaired by this technique, since collision will be calculated on inaccurate polygonal rep.
	NURBS tessellation	**1.0**	The highest *fsem* is for this technique, since the collision could be mathematically calculated with different accuracies.
	Valve Semantic Symbol	**0.2**	The symbols will not be accurate from a polygonal representation point of view, therefore the collision calculation would be inaccurate.

4.9 The Geometric Aesthetic Factor *fges*

This factor (with values between 0.0 and 1.0) complements *fsem* and has a numeric value used to quantify the *quality of the subjective geometric aesthetic perception linked with the acceptance of a 3D representation of a cell, independently from the functional / semantic value.*

In other words, this factor is the aesthetic counterpart of *fsem*.

As in the case of *fsem,* the concrete value of *fges* are somehow of subjective nature, but are useful to assign a numerical form for further mathematical treatment. This factor is helpful to *weight* also the techniques used to simplify semantically a model, taking into account appearance and aesthetic aspects. Not always *fsem* and *fges* reinforce each other, as a matter of fact, some techniques have opposite effects on both factors (see Table 3)

> *The value of* *fges* *quantifies the* ***subjective quality of the geometric aesthetic perception of a 3D representation*** *of a cell* $c_i \in S_i$ *, independently from the functional / semantic value, given a specific user purpose and profile* (0.0 is lowest, 1.0 is highest).

This factor can measure some undesirable effects (as for instance popping artifacts in non progressive Geometric LOD representations) which are not strictly of semantic-functional nature, but affect the way in which the user perceives the model in the walkthrough experience. The Table 3 shows, for the same examples used in *fsem* explanation, how the *fges* factor affects or weights the different techniques for a user purpose and user profile. The values of *fsem* are given as reference.

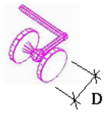
It is interesting to corroborate that *fsem* and *fges* can be high in one case and low in the other, depending on the user purpose and profile, and the technique used. This kind of knowledge will be very useful in the formulation of the mathematical optimization problem in the next section. These factors are calculated in the ***Semantic Adaptation Module*** (see Chapter 5.3) based on the knowledge provided by the ontologies of model, user and purpose.

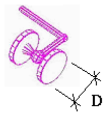
More formally:

$$fges = f(\text{user purpose, user profile, technique used, } c_i \in S_i)$$

(notice the similarity of parameters with fsem)

Table 3. Example of variability of *fges* values for the same cell with different user profiles, purposes and techniques.

Valve	**Technique**	***fges***	***fsem***	**Comment (of *fges*)**
	Brute force tessellation	**1.0**	**1.0**	The value of *fges* is the highest: a detailed representation is also aesthetically very good. Again, the drawback is on the high cost
	Geom LOD (½)	**0.7**	**1.0**	The graphical quality decreases. Semantically is also good.
User Profile: **Manager**	Drop Culling	**1.0**	**0.6**	No effect on the perceived quality of the model. The problem is loss of semantic.
User Purpose: **General Overview**	**Semantic Symbol**	**0.6**	**0.7**	A good symbol would convey also a good aesthetic result and perception, anyway less than the brute force tessellation

Valve	**Technique**	**fges**	**fsem**	**Comment (of fges)**
	Brute force tessellation	**1.0**	**1.0**	The most detailed representation is also the most pleasing geometric/aesthetic representation
	Geom LOD (½)	**0.5**	**1.0**	As he is an expert, the visual quality decreases notoriously.
User profile: **Piping Engineer**	Drop Culling	**0.4**	**0.0**	The visual quality of the model would be bad, since the expert would find it disturbing the absence of any valves.
Purpose: **Design Review**	**Semantic Symbol**	**0.9**	**0.9**	As an engineer used to work with symbols, the acceptance from the visual quality of the cell would be high.

Valve	**Technique**	**fges**	**fsem**	**Comment (of fges)**
User profile: **Manager/**	Brute force tessellation	**1.0**	**1.0**	The client typically wants to see a very detailed representation of all details of the plant, this technique allows it (with high cost).
Engineer	Geom LOD (½)	**0.2**	**0.5**	In this context the aesthetic aspects are critical. The client would expect a better graphical 3D representation.
Purpose:	Drop Culling	**0.8**	**0.0**	*fges* would be high since the visual quality is good for the client; the problem is that semantics are loss (*fsem* low).
Presentation to Client	**Semantic Symbol**	**0.7**	**0.5**	The client would probably understand well the symbols but the semantic / functional effect might be lower than expected

Valves and Pipes	**Technique**	**fges**	**fsem**	**Comment (of fges)**
	Brute force tessellation	**1.0**	**0.9**	The accuracy aspects affect mainly *fsem*, therefore *fges* is high.
User profile: **Structural Engineer**	Geom LOD (½)	**0.5**	**0.4**	As he is an expert, the visual quality decreases notoriously.
	NURBS tessellation	**1.0**	**1.0**	The tessellation accuracy of NURBS is typically high if the complexity of tessellation is set to high values.
Purpose: **Collision Detection**	**Semantic Symbol**	**0.8**	**0.2**	The engineer would have a good graphical representation but the visual quality does not correspond to the functional requirements.

4.10 The Tessellation and Simplification Techniques and the value Δt_i

We define T as the set of tessellation and simplification techniques $t_0, t_1, t_2, t_3, \ldots$ that can be applied to a cell c_i in $C,$ when prepared for the walkthrough experience in the ***Adaptive Representation Module.***

Notice that the cell c_i may belong to both the *classifiable set* S or even to the *non classifiable set* $\overline{S}$ *,* since actually *all* cells are somehow tessellated when a walkthrough is generated. However, only those cells $c_i \in S$ can be tessellated using techniques with higher adequacy for **semantic simplification**.

Some of the techniques in T can be applied to all cells, whereas some other techniques only apply to a specific type of cell. These techniques may range from the simple *brute force tessellation* (which basically produces a static polygonal representation of the cell under a given tolerance) to complex techniques such as the *NURBS tessellation* (which generate a parametric geometry to describe c_i) or the *Semantic Symbol tessellation.* More details on those techniques are found in chapter 5.4.

An important value that will be used in the mathematical model is the Δt_i value, which is related to the different geometry tessellation and simplification techniques when applied to a cell c_i. Basically, the strict definition of Δt_i is:

$$\Delta t_i (c_j) = \textit{number of triangles in the tessellation of } c_j$$

which of course depend on the technique used and the parameters (such as geometric accuracy) given to the tessellation.

As all cells in G_j share a geometric and semantic affinity, they should also behave similarly when a technique is applied.

We further simplify Δt_i for those cases when:

- t_i produces alternative representations that change during walkthrough (e.g. static or dynamic LOD)

$$\Delta t_i (c_j) \cong \textit{highest number of triangles among representations}$$

- t_i is actually applied to several cells to produce a single representation (e.g. *merging pipes* technique)

$\Delta t_i\ (c_j)\ \cong$ *average number of triangles evenly distributed to a single cell.*

Examples:

- In the case of static LOD, if a hypothetical cell would have alternatively 100, 300 and 1100 triangles depending on the switching condition, we would assign a Δt_i of **1100.**
- In the case of a technique merging elements (e.g. *merging pipes* technique) if the technique merges for example 7 sections of pipe for a total of 560 triangles, we would assign to each section a Δt_i of **80.**

But we know from the previous sections that the cells in the Plant Model can be classified, and that the ***Catalog Reconstruction Module*** is precisely in charge of such classification. Moreover, the ***ISO-STEP 10303-227 Adaptation Module*** group cells regarding their semantics in the standard domain of Plant Design.

Using this fact, we make an important simplification in the definition of Δt_i and relate it not to a single cell c_j, but to a complete *equivalence class* G_j :

$\Delta t_i\ (G_j) \cong$ (average) number of triangles when t_i is applied to any cell $c_i \in G_j$

Moreover, for those G_j that are part of one of the partition classes S_k of the *classifiable set* S (coming from the ISO-STEP 10303-227 Adaptation Module, see Chapter 5.2), we can also generalize Δt_i on S_k, so:

$\Delta t_i\ (S_k) \cong$ (average) number of triangles when t_i is applied to any cell $c_i \in S_k$

4.11 The Semantic Simplification Model as an Optimization Problem

So far we have introduced different mathematical concepts applied to the semantic simplification system. Now, we will use all the concepts described in this section to formulate, in a mathematical form:

> *A general optimization problem whose solution can answer the basic questions regarding the* ***application of semantic steered techniques*** *to a specific combination of mod****el characteristics, user profile/needs and available resources.***

This is, basically, a mathematical formulation of how the simplification techniques have to be applied optimally, considering semantic criteria, in order to solve the questions presented in the introduction of this chapter: optimal combination of techniques, influence of semantic aspects, impact, etc.

4.12 Focus on Object-based techniques instead space-based techniques

Before proceeding with the mathematical model, it is important to emphasize that my approach is focused on **object-based tessellation techniques**, **not on spatial distribution and culling techniques**.

It has been shown by several researchers (conspicuously the group of Dinesh Manocha in UNC, [MAN99]) that advanced *culling* and *spatial partitioning* techniques are indeed a key factor to achieve interactive rates in Design Review Walkthroughs for large 3D CAD models. Clearly, if a system manages to compute and send efficiently to the rendering pipeline only the visible elements in the current view, the possibility to get 10 fps or more is much more manageable taking into account two facts:

(i) Most of the times the user in a Plant Design walkthrough is looking attentively only to subsection with a small fraction of elements, and

(ii) The increasing processing power of the graphic cards is much closer to handle directly –without much optimizations- typical visible sets after efficient culling.

However it must be emphasized that an efficient use of the resources also depends heavily on the way in which the individual components are tessellated, with object based tessellation techniques. Actually the two dimensions are complementary and reinforce each other: therefore,

> *good culling and partition mechanisms, together with good semantic control on the object based tessellation techniques could give an improved walkthrough experience.*

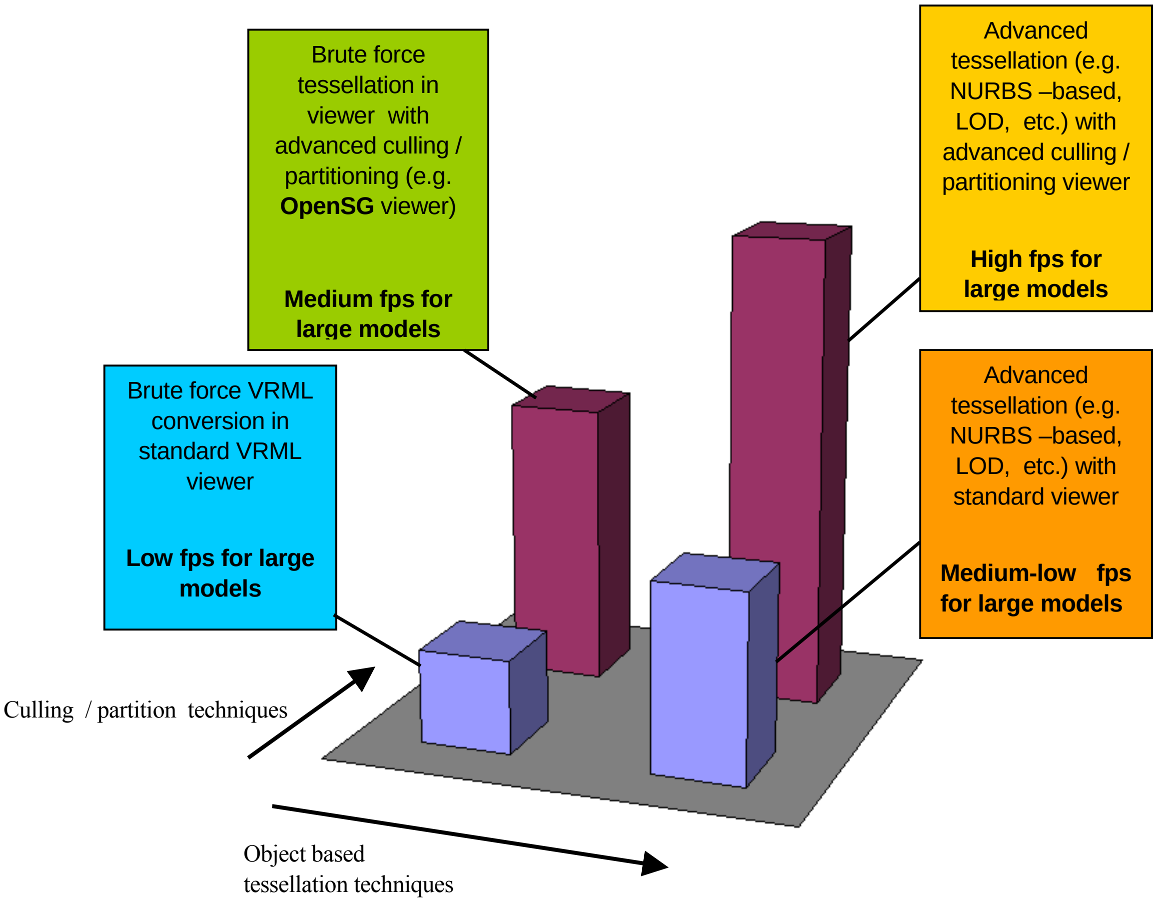


Figure 27. Example of the reciprocal influence between object-based and space-based techniques (vertical axis shows low/medium/high frames per second)

Thus, we **focus only on the *object based tessellation techniques*** assuming that good culling and partition techniques applied afterwards would provide an even better performance in the system.

4.13 The Semantic Simplification Mathematical Formulation

Using all the concepts introduced in this chapter, we present a formulation that allows a mathematical treatment of the fundamental problem:

> *how to apply optimally semantic steered simplification techniques for a walkthrough of a large model in the Plant Design domain, taking into account the user profile and user purpose, the model characteristics, and the available HW resources.*

We will introduce initially the incremental derivation for the mathematical formulation, and discuss it afterwards. First, let summarize the basic definitions in Table 4.

The approach presented in this work focuses in optimizing the way in which different techniques can be applied with semantic criteria to improve walkthrough experiences of 3D CAD Models.

The fact that we are looking for an optimal configuration based on the optional application of a set of discrete techniques and context characteristics, led this research towards the field of Quantitative Methods for engineering, more specifically, to the **Integer Programming** method. This will be a basic underlying model.

Obviously one of the most important factors for a successful walkthrough is that the fps achieve fluid interactive rates (authors differ in the exact value, but is widely accepted that fps above 10-15 are interactive). However, this must not be the only criteria to take into account, as we have discussed before. An initial approach would be to define an ***objective function*** such as:

$$\textit{maximize } fps\ (P) \quad \text{s.t.} \quad \begin{array}{l} \textit{semantic criteria restrictions} \\ \textit{user profile} \\ \textit{user purpose} \\ \textit{available resources} \end{array}$$

However, finding a tractable and well constrained formulation for fps is a difficult task for the proposed methodology, because:

(i) it is an instantaneous changing value during the walkthrough, not a persistent value that can be controlled more easily.

(ii) the correlation of all involved aspects (HW resources, complexity of the Scene Graph to render, culling weights, changing number of triangles in the budget, etc.) is entangled and not easily adapted to an integer programming schema.

(iii) The complexity of the other factors would hide the specific focus on semantic simplification benefits.

Table 4. Definitions for the mathematical formulation of the Semantic Simplification

P	be a 3D CAD model of an Industrial Plant
$PS \subset P$	be a spatial subsection of interest –*subset*- of a 3D plant (*spatial* means constrained by spatial limits, as after culling).
$fps(PS)$	be the instantaneous Frames Per Second value that a walkthrough would produce when PS is navigated.
$tris(PS)$ $tris(S_i)$ $tris(G_i)$	be the total number of triangles generated by **all** *cells* in PS be the number of triangles generated by **all** *cells* in S_i be the number of triangles generated by **all** *cells* in G_i
G_j	be an *equivalence class* from the Catalog Reconstruction Module
nG_j	be the number of *cells* of the *equivalence class* G_j in PS
Δtg_{ij}	be the(average) number of triangles when t_i is applied to one representative cell $c \in G_j$
S_k	be a *partition class* from the ISO-STEP Adaptation Module
nS_k	be the number of *cells* of the *partition class* S_k in PS
Δts_{ik}	be the(average) number of triangles when t_i is applied to one representative cell $c \in S_k$
T	be the set of object-based tessellation techniques available $T = \{ t_0, t_1, t_2, t_3, \dots \}$
t_i	be the i-th object-based tessellation technique available.
t_0	be the default case: t_0 as the **brute force tessellation** technique
x_{pq}	be the **Decision Variable:** $x_{pq} = 1$ if technique t_p should be applied to all cells in S_q $x_{pq} = 0$ otherwise
q_i	be the number of cells (*cardinality*) of S_i ($q_i = nS_i$)
p	be the number of cells (*cardinality*) of P
q_i / p	be the *cell concentration* of class i for the Plant P
qs_i / ps	be the *cell concentration* of class i for a Plant Section PS
$fsem_{pq}$	be the *Functional Semantic factor* of t_p when applied to a $c \in S_q$ $fsem = f($user purpose, user profile, technique used, $c \in S_q)$ (obtained from the *Semantic Adaptation Module*)
$fges_{pq}$	be the *Geometric Aesthetic factor* of t_p when applied to a $c \in S_q$ $fges = f($user purpose, user profile, technique used, $c \in S_q)$ (also obtained from the *Semantic Adaptation Module*)

Therefore, and taking into account that the instantaneous value of $fps\ (P)$ is directly related to the $tris(PS)$ for each PS visited (and in a less important way to the available resources, processing time, structure of the scene graph and other variables), we reformulate the *objective function* so:

$$minimize\ \ tris\ (P) \qquad \text{s.t.} \qquad \begin{array}{l} \textit{semantic criteria restrictions} \\ \textit{user profile} \\ \textit{user purpose} \\ \textit{available resources} \end{array}$$

This is, we keep the restrictions but take a different *objective function.* Let´s elaborate the mathematical expression for $tris\ (P)$:

minimize

$$tris\ (P) = \underbrace{tris(S_0) + tris(S_1) + \ldots + tris(S_n)}_{\text{Triangles produced by all } \textit{partition classes} \text{ related to STEP standard (} \textit{ISO-STEP Adaptation Module} \text{)}} + \underbrace{tris(\overline{S})}_{\text{Triangles in the } \textit{non classifiable} \text{ set (but in equivalence classes Gi from } \textit{Catalog Reconstruction Module} \text{)}}$$

s.t. *semantic criteria restrictions, user profile user purpose, available resources*

Let´s point out that $tris(S_k) = nS_k \cdot \Delta ts_{ik}$ if t_i is used for tessellation. Notice that this is an approximate value, but good enough for practical applications. On the other hand, we will consider that:

$$tris(\overline{S}) = \sum_{i=0}^{m} nG_i \cdot \Delta tg_{\mathbf{0}i} \cdot \text{bool}\ (G_i \subset \overline{S})$$

since all the cells in the *non classifiable set* $\overline{S}$ are tessellated using the *brute force tessellation technique* t_0. Thus the *objective function* can be rewritten as:

minimize

$$tris\ (P) = [nS_0 \cdot \Delta ts_{a0})] + [nS_1 \cdot \Delta ts_{b1}] + \ldots + [nS_n \cdot \Delta ts_{zn})] + \sum_{i=0}^{m} nG_i \cdot \Delta tg_{0i} \cdot \text{bool}\ (G_i \subset \overline{S})$$

s.t. *semantic criteria restrictions, user profile user purpose,available resources* where we do not know yet which specific techniques are $t_a, t_b, \ldots, t_z$ for each S_i.

This is actually the missing factor in the formulation of the objective function: to include somehow **decision variables** that are related with the specific techniques selected for each partition class. Therefore we introduce:

x_{pq} as the **Decision Variable:**

$x_{pq} = 1$ if technique t_p should be applied to all cells in S_q

$x_{pq} = 0$ otherwise

Thus the *objective function* is now (assuming $z+1$ techniques and $w+1$ partition classes, and grouping similar terms):

minimize

$$
\begin{aligned}
tris\,(P) = {} & nS_0 \cdot [x_{00} \cdot \Delta ts_{00} + x_{10} \cdot \Delta ts_{10} + x_{20} \cdot \Delta ts_{20} + \ldots + x_{z0} \cdot \Delta ts_{z0}] + \\
& nS_1 \cdot [x_{01} \cdot \Delta ts_{01} + x_{11} \cdot \Delta ts_{11} + x_{21} \cdot \Delta ts_{21} + \ldots + x_{z1} \cdot \Delta ts_{z1}] + \\
& nS_2 \cdot [x_{02} \cdot \Delta ts_{02} + x_{12} \cdot \Delta ts_{12} + x_{22} \cdot \Delta ts_{22} + \ldots + x_{z2} \cdot \Delta ts_{z2}] + \\
& \ldots \\
& nS_w \cdot [x_{0w} \cdot \Delta ts_{0w} + x_{1w} \cdot \Delta ts_{1w} + x_{2w} \cdot \Delta ts_{2w} + \ldots + x_{zw} \cdot \Delta ts_{zw}] + \\
& \sum_{i=0}^{m} nG_i \cdot \Delta tg_{0i} \cdot \mathrm{bool}\,(G_i \subset \overline{S}\,)
\end{aligned}
$$

s.t. *semantic criteria restrictions, user profile user purpose, available resources*

Some things are important to highlight at this point:

(i) Evidently, only **one** technique is applied for every S_i; this means that only one x_{ij} will be 1 for every i (the other x_{ij} will be 0).

(ii) The last term (related with the triangles produced by $\overline{S}$) would be considered as a constant factor in the optimization problem, since it is not affected by any decision variable.

(iii) This last term, however, has one associated restriction, related with the consideration that too many triangles produced by $\overline{S}$ actually mean that the catalog reconstruction and classification from standard is not good enough to continue with the process. This will be explained below in this section.

(iv) From the z techniques available, not all are applicable to every partition class in S. This will be also explained below as a *constraint*.

4.14 A predictive variant of the objective function based on cell concentrations *qi/p*

In the current form, the objective function depends on the number of cells nS_i of each partition class for a specific P. This form is useful in case there are enough resources to **actually count** the number of elements in a plant P or in a plant section PS as well as in every partition class S_i. This of course would give a more accurate value for $tris\ (P)$. Notice that in the case of plant sections PS, these values should be calculated constantly in real time for different PS in a walkthrough.

However, in many cases it is useful to have as well a **predictive** variant of the objective function that doesn't require a constant calculation of nS_i for all PS. Furthermore, it would be useful to have a simplification of the *objective function* that could be applied to:

- several models of plants P of the same domain, or
- different sections PS of the same plant P

My approach in this direction is based on the *Postulate 2* and *Postulate 3* presented in the *cell concentration* section:

- *The values of all* q_i/p *tend to have similar values, within some limits, between different 3D CAD models of the same domain (in this case Plant Design), independently from the modeller used or the size of the model.*

- *If* PS *is a spatial subsection of a complete plant* P*, then* qs_i/ps *has the general tendency to be similar to* q_i/p (*thus:* $qs_i/ps \cong q_i/p$)

Thus, we divide the whole *objective function* by the total number of cells p of the plant, and considering that

$$q_i/p = nS_i\,/\,p$$

we obtain then the **simplified *objective function* in terms of *cell concentration*:**

minimize

$$\frac{tris\,(P)}{p} = q_0/p \cdot [x_{00}\cdot \Delta ts_{00} + x_{10}\cdot \Delta ts_{10} + x_{20}\cdot \Delta ts_{20} + \ldots + x_{z0}\cdot \Delta ts_{z0}] +$$

$$q_1/p \cdot [x_{01}\cdot \Delta ts_{01} + x_{11}\cdot \Delta ts_{11} + x_{21}\cdot \Delta ts_{21} + \ldots + x_{z1}\cdot \Delta ts_{z1}] +$$

$$q_2/p \cdot [x_{02}\cdot \Delta ts_{02} + x_{12}\cdot \Delta ts_{12} + x_{22}\cdot \Delta ts_{22} + \ldots + x_{z2}\cdot \Delta ts_{z2}] +$$

$$\ldots$$

$$q_w/p \cdot [x_{0w}\cdot \Delta ts_{0w} + x_{1w}\cdot \Delta ts_{1w} + x_{2w}\cdot \Delta ts_{2w} + \ldots + x_{zw}\cdot \Delta ts_{zw}] +$$

$$1/p \cdot \sum_{i=0}^{m} nG_i \cdot \Delta tg_{0i} \cdot \mathrm{bool}\,(G_i \subset S)$$

s.t. ***semantic criteria restrictions, user profile user purpose, available resources***

which is a simple but powerful expression of the objective function. Before detailing the *constraints*, let's discuss some of the advantages and disadvantages of this simplified form for the *objective function:*

1. This is a **persistent formulation of the objective function** with regard to both the <u>whole</u> plant P (<u>static</u>) and <u>representative plant sections</u> during walkthrough (<u>dynamic</u>) $PS \subset P$. This is easily done replacing the expression $tris(P)/p$ by $tris(PS)/ps$, and q_i/p by qs_i/ps (by *postulate 3* in cell concentration section). The nice consequence is that with a **single objective function for the whole plant** P we can **predict** (approximately) the behaviour of most sections $PS \subset P$ during walkthrough. Notice that the last term at the right side remains basically a constant.

2. This means also that the application of techniques t_i can be done **statically** during the conversion process (which is previous to the walkthrough), since the objective function is basically the same for the whole plant and its sections. In other words, this formulation shows that any *potential improvement of dynamic change of one technique to another* for the cells of an instantaneous plant section **is not worthwhile**.

3. If there is enough statistical treatment of the *cell concentrations* (for different but representative 3D CAD models of the Plant Design domain), **approximate values of q_i/p** (e.g. means with some variation) **could be pre-calculated**. This would provide a way to proceed directly with the optimization function without the need of actually counting the number of cells of a specific plant / section (although this should not be very costly). This is also a consequence of the fact that the 3D CAD models belong to a well structured domain where all models share similar characteristics independently from the modeller used or the size of the model.

4. Expressed in this form, the objective function is actually expressing the inner structure of the **distribution** of standard components of a plant or plant section, letting the optimization weight basically the <u>optimal cost in number of triangles</u> based on the technique applied to each component (the *constraints* will balance this including semantic aspects).

4.15 Elaboration of the constraints of the optimization problem

Once we have the *objective function* to minimize, we will now develop further the ***constraints*** of the *optimization* problem, assuming z+1 techniques and w+1 partition classes:

Constraint 1:

Exactly one technique should be applied to the cells of a class partition S_i

$$\sum_{j=0}^{z} \mathbf{x_{ij}} = 1 \qquad \text{(for any fixed i between 0 and } w\text{)}$$

Constraint 2:

Some techniques are not applicable to all S_i

Ex: the *pipe merging technique* only apply to cells in the *straight pipes* partition class, the *NURBS tessellation* technique only apply to certain parts of the model, etc. Let's suppose that technique t_a can not be applied to S_b. This is written as a restriction of the type:

$$\mathbf{x_{ab}} = 0$$

Equivalently, the term $x_{ab} \cdot \Delta ts_{ab}$ can be eliminated from the objective function.

Constraint 3

The tessellation of $\overline{S}$ *should not produce too many triangles (above a given threshold); otherwise the brute force tessellation of* $\overline{S}$ *would occlude any benefits coming from semantic simplification in* S*.*

This can be written as ($\boldsymbol{th}$ is the given threshold):

$$tris(\overline{S}) \,/\, tris(P) \leq th \qquad (\text{heuristically, } th \cong 0.3)$$

Actually, if this constraint is not fulfilled, it would mean that the catalog reconstruction and classification from STEP standard *are not good enough to bring tangible benefits from semantic simplification*.

Constraint 4:

The **Adaptive Representation Module** *generates, based on the available ontologies for* *user purpose, user profile, model characteristics, and available resources, a set of lower limits for the*

$$fsem \text{ and } fges \text{ values of any } t_i$$

for each S_i. *This set of values can be user to write a constraint of the optimization problem.*

This is an important output from the adaptive representation module. It actually provides the minimum values for *fsem* and *fges* for each technique, *taking into account the semantic conditions of the problem.* This is later translated into a constraint for the optimization problem.

In general, if we have $w+1$ partition classes, the ***constraints*** associated to $fsem$ and $fges$, defined in the Adaptive Representation module, are expressed in the following way:

$$fsem\,(S_i) \le a_i \quad fges(S_i) \le b_i$$

where a_i, b_i are values for each S_i, and

i goes from 0 to w

A simple example can illustrate this process better. Let's suppose that a **piping engineer** is interested in a **design review** purpose for a model of an **industrial chemical plant**. Let S_0 be the partition class related with ISO-STEP **valves** and S_1 be the partition class related with ISO-STEP **beams.**

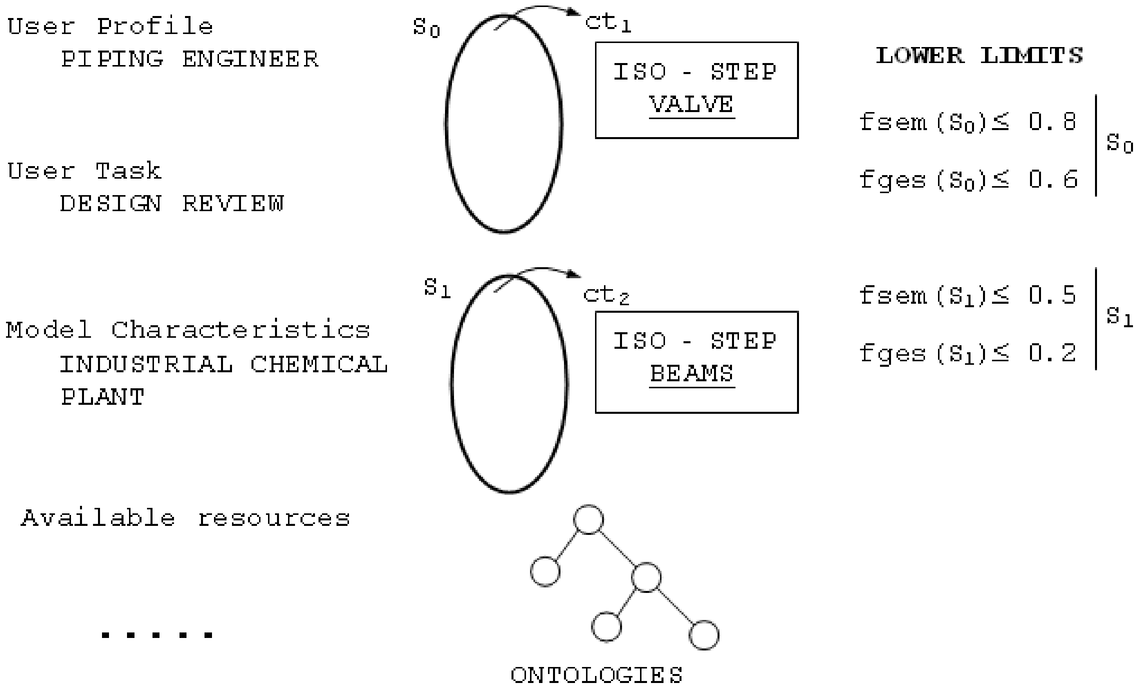


Figure 28. Examples of some constraints calculated in the *Adaptive Representation Module*

With the above considerations, the constraints from the Adaptive Representation Module, associated to minimum values for *fsem* and *fges,* would be for instance:

$$fsem\ (S_0)\ \leq 0.8$$
$$fges\ \ (S_0)\ \leq 0.6$$

(it is important for **any** technique applied to S_0 that the functional semantic factor is very high; this is what a piping engineer would expect in a design review purpose for valve components. In this case, also high values would be expected for *fges*)

Similarly,

$$fsem\ (S_1) \leq 0.5$$
$$fges\ \ (S_1) \leq 0.2$$

(as beams are not the focus of the piping engineer in a design review, notice that the minimum values have lower thresholds.)

This is the way in which the ***constraints* are defined** by the adaptive representation module.

The ontologies also help to produce explicitly the different $fges_{pq}$. In the example, if we only consider 3 techniques: t_0 is **brute force tessellation**, t_1 **drop culling,** t_2 **semantic symbols (**for a **piping engineer** in a **design review** purpose) we would obtain (see Table 3) for example the values:

$$fsem_{00} = 1.0 \quad fsem_{10} = 0.0 \quad fsem_{20} = 0.9$$

$$fges_{00} = 1.0 \quad fges_{10} = 0.4 \quad fges_{20} = 0.9$$

and

$$fsem_{01} = 1.0 \quad fsem_{11} = 0.0 \quad fsem_{21} = 0.8$$

$$fges_{01} = 1.0 \quad fges_{11} = 0.3 \quad fges_{21} = 0.5$$

The optimization problem would be in charge of selecting the right techniques considering these constraints (in this concrete example t_0 and t_2 could be candidates for both S_0 and S_1, but not t_1).

Constraint 5:

So far we have constraints related with the model and with the user background and intention. The following constraints are related to the **resources** available in the system, especially:

(i) *graphic card capability*

(ii) *available memory* (*RAM, HD*)

(iii) *processing power*

We will follow a **conservative** approach to those constraints as explained below. More constraints could also be included; we show a generic methodology to include these aspects in the optimization problem.

These two first *resources constraints* actually depend heavily on the **number of triangles** generated in the plant P and in each of the different Plant Sections PS. Let's recall that the *objective function* to optimize is precisely expressed in terms of this quantity ($tris\ (P)\ /\ p$). Clearly, the objective of the optimization problem is not just to minimize that expression, but *to guarantee that the minimal solution fulfils the available resources.*

These constraints can be written in the following form:

<u>*Graphic Card capability*</u>: We call $\boldsymbol{gc_{max}}$ to the maximum value of **tris/second** of the graphic card. This is a widely known criterion to measure the performance of a graphic card, which somehow summarizes the effect of several internal characteristics such as *card memory, Open GL acceleration, etc.* If we assume **10** to **15** fps as an interactive rate for the walkthrough, with a section PS being rendered, and that the cf is an average **culling factor** (let's take a **low** value to be conservative; $cf \cong 1.2$) to the *object based techniques*, we could say that each of the Plant Sections PS should be rendered at that rate, thus:

$$tris\ (PS)\ /\ cf \quad \leq \quad \boldsymbol{gc_{max}}\ /\ fps \quad ,$$ which is approx.

Assigning conservative values,

$$tris\ (PS)\ /\ 1.2 \quad \leq \quad \boldsymbol{gc_{max}}\ /\ 15.0 \quad \text{(conservative values)}$$
$$tris\ (PS) \quad \leq \quad 0.08\ \boldsymbol{gc_{max}}$$

It is interesting to notice that the evolution of $\boldsymbol{gc_{max}}$ is incredible fast : five years ago was about **5 Mtris/sec** (GeForce 256) and today is about **800 Mtris/sec** -e.g. NVIDIA GFORCE 7800!)

This is of course not considering that the numbers given by the card manufacturer are obtained in very favourable conditions (e.g. all triangles in very few tristrips), therefore the value of $\boldsymbol{gc_{max}}$ should be also conservative –lower than the "official" number-.

<u>*Available Memory capability*</u>: This is also a critical factor, and it is difficult to separate it from the *processing power and memory speed access* when good **fetching and out of core** strategies (as discussed by [CORR04]) are applied. These *fetching* strategies are based on the fact that <u>not all</u> the model is loaded in RAM memory, but only necessary

part sections PS are processed and fetched from hard disk. This has an additional cost of processing power and lower access speed, but with the clear advantage that **much less RAM is required** since only a fraction of the model is loaded in real time in RAM.

There is a level of complexity in which *fetching* is not only an option but almost a requirement (since simulation of RAM on hard disk would decrease performance abruptly): **when the number of triangles of the whole model exceed anyway the available RAM**. This could happen either in very limited HW (e.g. PDAs, old computers) or in huge models (e.g. more than 10^8 triangles).

This also depends on how efficiently the information is encoded. A brute force tessellation + NURBS tessellation of a large Plant Design model, including redundancies in memory, all hierarchical/structural information in the scene graph, colours, textures, LODs, etc., could give very high memory consumption rates per triangle as shown in Table 5, especially if there is no focus on geometry compression techniques. The table shows 2 real examples rendered with **TGS Open Inventor**. Notice that these numbers are **not** comparable to typical meshes in literature: nice complex objects in a single large mesh with several tristrips (e.g. Buddha, rabbit) which without optimization give approximately **50 bytes & triangle.**

Table 5. Bytes per triangle (not optimized) in representative Plant Sections in Open Inventor. Similar data also obtained in OpenSG.

Model	CAD format space in HD	Converted to Inventor Space in HD (text format)	Nodes	Triangles	RAM Memory	Bytes / triangle in RAM
PS 1	32,15 MB	15,5 MB	182.884	2.568.975	410 MB	**159,61**
PS 2	26,23 MB	24,1 MB	285.560	3.862.601	617 MB	**162,63**

Thus, values of 160 bytes/triangle and higher can be found in those cases. More efficient viewers can obtain much better rates: In some implementations I have tested based on OpenSG I have got results under 90 bytes/triangle for the same models, and it is accepted in the research community that values of about 50 bytes/triangle per triangle are normal if no overhead is considered (this is, only geometry and connectivity).

Special simplification techniques (conspicuously **geometry compression** techniques) have been introduced by Deering, Taubin, Rossignac, Grossman, Isenburg, etc., that are able to code triangle meshes with connectivity coded in 1–2 bits per triangle, and use a linear predictor to compress vertex data to 5–10 bytes per triangle, for a total of about **7-12** bits per triangle [HOP99]. These techniques reduce in a factor from 6 to 10 those two aspects. However these techniques require a good amount of pre-processing and do not consider structure-hierarchy, colour/texture information, etc., just geometry and connectivity.

As a conclusion, and in order to simplify the constraint expression, I will assume the following: the **constraint should guarantee that Plant Section PS fits into the available RAM;** at least if no out-of-core architectures are considered. Although an efficient implementation could give a much better rate, we take the (very) conservative value of *bytes per triangle* (bpt) of 160 bytes/triangle for this. The available RAM in bytes will be called $aRAM$.

$$tris(PS) \cdot bpt \leq aRAM$$

With very conservative values, without geometry compression techniques, this would be:

$$tris(PS) \cdot 160 \leq aRAM$$

With relation to the Hard Disk capabilities, it is a resource where typical storage values are very high (and increasing at Moore's Law or faster). Even a verbose description language such as **VRML 2.0** would give quite acceptable rates for storage in typical PC scenarios (at about **35000 triangles / MB**), although this can dramatically decrease using compression schemas combining geometry compression and Huffman coding. If we let aHD be the available Hard Disk space in Megabytes, and $tpMB$ the triangles per megabyte in hard disk, this would be the restriction:

$$tris(P) \leq tpMB \cdot aHD$$

But for the conservative case:

$$tris(P) \leq 35000 \frac{tri}{MB} \cdot \mathrm{HD}$$

<u>Processing Capabilities</u>: More and more the processing of the scene graph to render is done actually in the graphic card. However, several aspects remain controlled by the CPU, and if it is not powerful enough, could be the bottleneck of the whole process. The main tasks of the CPU could be for example, handling of the hierarchical node structure,

calculation of culling mechanisms, fetching control, LOD control, interaction for input devices, etc.

To simplify a constraint that takes into account this factor, we relate the required processing capabilities also with the number of triangles in the model $tris\ (P)$. If we let $tpMHz$ be the approximate value in triangles per Megahertz that the CPU can handle in typical models, and $aCPU$ the available CPU power in Megahertz, we would have:

$$tris(PS) \leq tpMHz \cdot aCPU$$

Heuristically, we have found a conservative estimation for $tpMHz$:

$$tpMHz \approx 1500 \frac{tris}{MHz}$$

which is a very rough simplification (the behaviour is actually not linear, and depends very much on implementation efficiency) but fits into the ranges and observations we have found for large models in plant design.

4.16 Summary of the Mathematical Formulation

With both the *objective function* and the *constraints* explained, we can summarize the formulation of the *optimization problem* (see Figure 28) in the simplified form. Notice that a similar formula can be given for a exact calculation of the individual nS_i according to formula in Chapter 4.13. The values of $th,\ cf,\ gcmax,\ fps,\ bpt,\ aRAM,\ aCPU,\ aHD,\ tpMB,\ tpHZ$ can be updated according to the evolution of resources and algorithms. In the pages above, I have given approximate values up-to-date.

For z+1 techniques and w+1 partition classes, find the values of the decision variables $\mathbf{x_{ij}}$ that:

minimize

$$\frac{tris\,(P)}{p} = q_0/p\cdot[x_{00}\cdot\Delta ts_{00}+x_{10}\cdot\Delta ts_{10}+x_{20}\cdot\Delta ts_{20}+\ldots+x_{z0}\cdot\Delta ts_{z0}]+$$

$$q_1/p\cdot[x_{01}\cdot\Delta ts_{01}+x_{11}\cdot\Delta ts_{11}+x_{21}\cdot\Delta ts_{21}+\ldots+x_{z1}\cdot\Delta ts_{z1}]+$$

$$q_2/p\cdot[x_{02}\cdot\Delta ts_{02}+x_{12}\cdot\Delta ts_{12}+x_{22}\cdot\Delta ts_{22}+\ldots+x_{z2}\cdot\Delta ts_{z2}]+$$

$$\ldots$$

$$q_w/p\cdot[x_{0w}\cdot\Delta ts_{0w}+x_{1w}\cdot\Delta ts_{1w}+x_{2w}\cdot\Delta ts_{2w}+\ldots+x_{zw}\cdot\Delta ts_{zw}]+$$

$$1/p\cdot\sum_{i=0}^{m} nG_i\cdot\Delta tg_{0i}\cdot \mathrm{bool}\,(G_i\subset\overline{S})$$

s.t.

(c1) $\sum_{j=0}^{z}\mathbf{x_{ij}}=1$ (for any fixed i between 0 and w)

(c2) $\mathbf{x_{ab}}=0$ (for any technique t_a not applicable to S_b)

(c3) $tris(\overline{S})\,/\,tris(P) \leq th$

(c4) $fsem\,(S_i)\leq a_i \quad fges(S_i)\leq b_i$

(from the *Adaptive Representation Module*)

a_i, b_i are values for each S_i, and i goes from 0 to w

(c5)

$$tris\,(PS)\,/\,cf \leq \mathbf{gc_{max}}\,/\,fps$$

$$tris(PS)\cdot bpt \leq aRAM$$

$$tris(P) \leq tpMB\cdot aHD$$

$$tris(PS) \leq tpMHz\cdot aCPU$$

Figure 29. Mathematical formulation of the optimization problem for semantically steered techniques

4.17 Comments on the Solution to the Optimization Problem

For the solution and application of the *optimization problem* above on the walkthrough of a specific P, I follow this approach:

1. Following the architecture of the system, we find the **equivalence classes** G_i for P using the **Catalog Reconstruction Module.**
2. We find the **set partition classes** S_j corresponding to the ISO-STEP standard by means of the **ISO-STEP 10303 Adaptation Module,** as well as the subset $\overline{S}$ **.**
3. In the **Semantic Adaptation Module** as well as the **Adaptive Representation Module** actually are in charge of *solving* the optimization problem and give the appropriate techniques and parameters to apply to the different partition classes. Notice that **every single step has a semantic background**:

    a. From the ontology of ISO-STEP elements, the average number of triangles Δts_{ij} to represent a part with different techniques is obtained. In case it is unknown, a representative is tessellated and actually measured.

    b. In case the simplified form is preferred (based on q_i /p) the *cell concentrations* q_i/p are taken from the ontology as typical values for the domain. Otherwise the values $q_i = nS_i$ are actually calculated (a simple *cardinality* operation on S_i) for the exact form.

    c. Constraints 3 and 5 have the special characteristic that they actually depend on $tris(P)$ or $tris\ (PS)$ which is also part of the left side of the optimization problem. **Therefore they should not be included** in the initial algorithm for the solution of the problem (cyclic solution), but are considered **after** the optimization problem is solved with constraints 1,2 and 4.

    Then, it can be compared if the correspondent values for $tris(P)$ or $tris\ (PS)$ are between the limits that constraints 3 and 5 establish. If not, it would mean that a minimum has been found, but it is either:

i. Not very efficient due to high proportion of brute force tessellation (constraint 3), or

ii. It is not feasible for the existing resources (constraint 5).

This would require then:

i. In case that just constraint 3 is violated, it is anyway a valid solution; the only problem is that the semantic techniques bring little improvement to that model.

ii. In case constraint 5 is violated, the situation is more serious: a resource constraint has to be relaxed or more resources are required, accordingly.

d. The lower limits for $fsem$ and $fges$ are obtained from the ontologies, as well as the values for $fsem_{ij}$ and $fges_{ij}$ for the specific conditions of user purpose, user profile and model characteristics.

e. The problem is solved with **integer programming** techniques. If there is at least one valid minimum solution, the **decision variables x_{ij}** indicate which techniques are applied to the respective cells in the set partitions. Thus, the walkthrough is conditions are prepared.

4.18 Conclusions of this chapter

In this chapter I have introduced a mathematical model that corresponds to the underlying relations of the different modules of the proposed methodology to adapt large CAD models of Industrial Plants for visualization walkthroughs.

This mathematical model gives objective criteria to decide when and how to apply semantic-steered techniques for the simplification.

At the same time, it allows the evaluation and quantitative measurement of the effective influence of the semantic approach in the walkthrough generation

We have used set theory and optimization theory in order to give a foundation to the methodology and the architecture of the implementation of the MiroWalk system, which is explained in Chapter 0.

The methodology as well as the mathematical model can be extended to be more comprehensive or efficient, but the basic elements to consider are already included in the formulation.

5 GENERIC ARCHITECTURE AND SYSTEM IMPLEMENTATION OF SEMANTIC VISUALIZATION WALKTHROUGHS FOR PLANT DESIGN

In this chapter I present the architecture of the proposed methodology for generation of walkthroughs for Plant Design models, which includes the different semantic and computer graphics aspects described in other sections of this work. I use semantic compression added to simplification techniques of the geometrical data to increase the efficiency and complement the traditional Computer Graphics methods in the field, including semantic aspects.

It is important to recall that the proposed architecture is tightly related with the **mathematical model** of Chapter 4 , which describes the relationships and processes in the architecture models from a mathematical, generic perspective.

We take as a starting point any proprietary geometric 3D CAD representation of an industrial plant. It is deliberately assumed that no other information is available (e.g. from a modern PIM system) since for many reasons –legacy data, database model exchange between companies, etc.- this is the general case.

We then reconstruct automatically the families of engineering parts in the model, associate those families to the standard, introduce both geometric and semantic object simplification techniques, and present the adapted plant model in an interactive system for design review walkthroughs.

Thus, in this chapter all the different considerations about the underlying mathematical model (Chapter 4), the relationship of the STEP standard and the ontology of Industrial Plant Design (Chapter 3), etc. acquire a concretion in an integrated system architecture.

As a result,

- I have defined this architecture (whose modules are explained in detail in this chapter) with a modular approach in which the relevance of semantic aspects is more evident

- I have implemented a software system, the **MiroWalk system**, that includes an advanced implementation of the architecture described, and is fully functional and complete system that applies the methodology described in this thesis to real world CAD models of industrial plants.

Each module in the architecture is explained in detail in the following subchapters. The overall architecture of the system can be seen in Figure 30.

The 3D CAD Model is thus processed in such a way that each module adds up a different and complementary semantic dimension to the final model used in the visualization.

Thus, to make a very simplified description, the *Catalog Reconstruction Module* introduces the *spatial instancing* explicitly, for those cases in which the 3D CAD model does not hold this information (which is a common situation).

The *ISO-STEP 10303-AP227 Adaptation Module* classifies the instances in the model into categories corresponding to the STEP standard of Industrial Plant Design. The *Semantic Adaptation Module* takes into account the adapted model as well as the available resources, the user profile and the visualization walkthrough purpose, and applies the *semantic triangle* criteria (Figure 10) to generate parameters to select appropriate techniques for rendering.

The *Adaptive Representation Module* selects and applies the best tessellation and rendering techniques to use during the visualization walkthrough, based on the criteria and parameters of the previous module.

Finally, the *Semantic Visualization Walkthrough Module* is in charge of producing for the user the interactive walkthrough of the adapted model using the available resources, and considering the domain and purpose involved.

Figure 30 shows the modules of the architecture and the relationships between them. This figure will be the reference to explain in detail each module.

It is necessary to stress that the modules are *generic* in nature, and extensible to include refinements in different directions. The most important aspect of this architecture is not its current implementation in one system, but the fact that the modular structure presented is the basis of a generic methodology for the semantic adaptations of 3D CAD models in the domain of Plant Design (or even other domains).

Thus, specific algorithmic improvements (e.g. new shape similarity algorithms in the *Catalog Reconstruction* Module), better semantic reasoning aspects (e.g. automatic prediction of user intention), more comprehensive inclusion of rendering/simplification techniques in the *Adaptive Representation Module* (e.g. fast progressive meshes, PBR) are always possible, without loss of generality.

I present in this chapter the basic concepts behind each module, as well as the selected implementation approaches used in the *MiroWalk* system, as integrated, proof of concept system that applies the methodology.

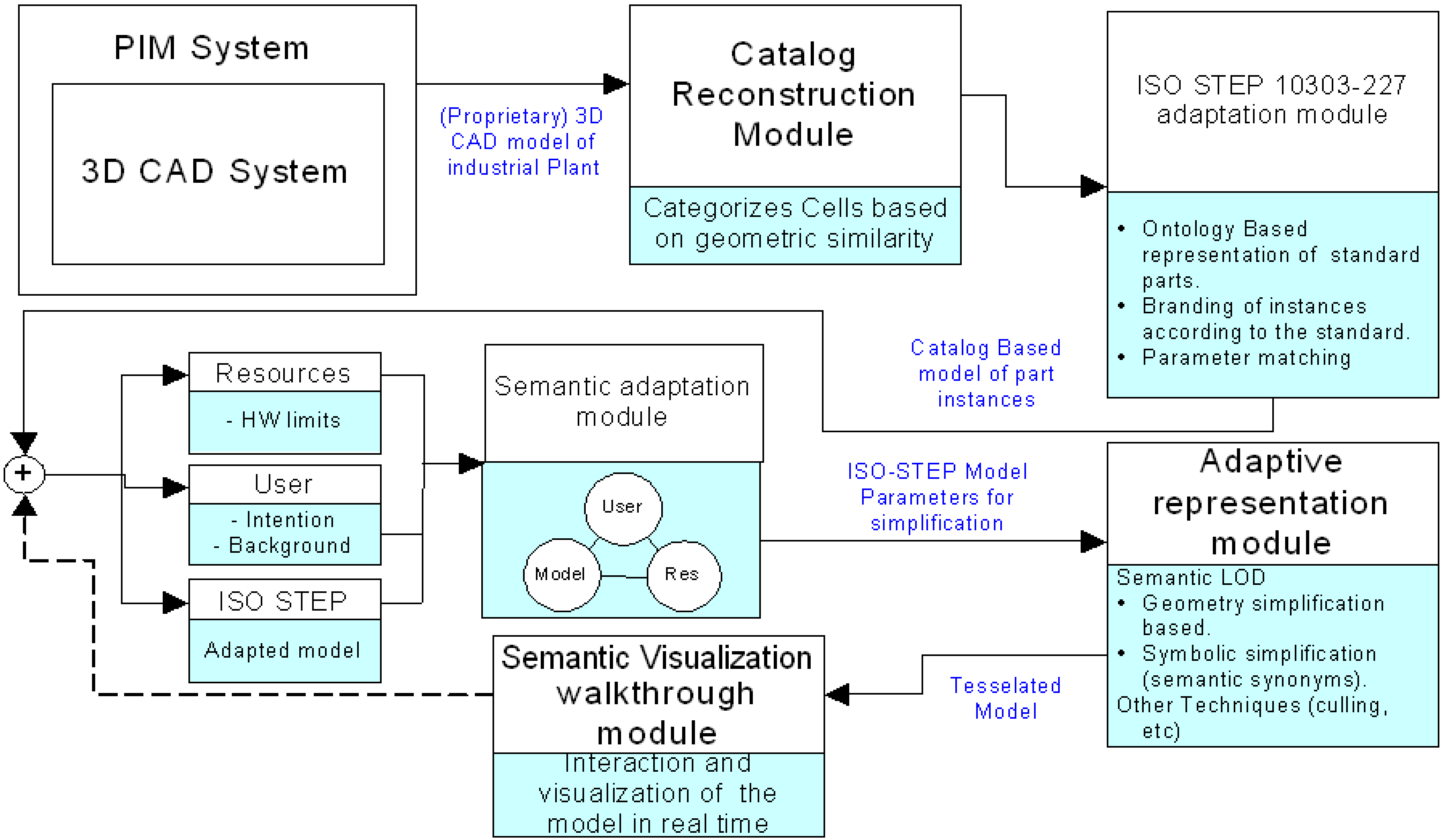


Figure 30. Methodology and Architecture for the Semantic Visualization of Industrial Plant Models- complete view of all modules, relations and involved parameters

5.1 THE CATALOG RECONSTRUCTION MODULE

This module traverses the 3D CAD model identifying groups of geometric primitives (we call these groups/families ***cells,*** see Chapter 4 for more details) automatically, and categorizes them in groups based on geometric similarity. The 3D CAD model creation in the domain of Plant Design is based in the parametric definition and selection of appropriate engineering parts (e.g. valves, pipe sections, etc.) from specific catalogues. However, the resulting CAD models usually do not contain any explicit instancing information, and the first step towards an increased semantic representation of the model is to group these cells using the cell-matching algorithm.

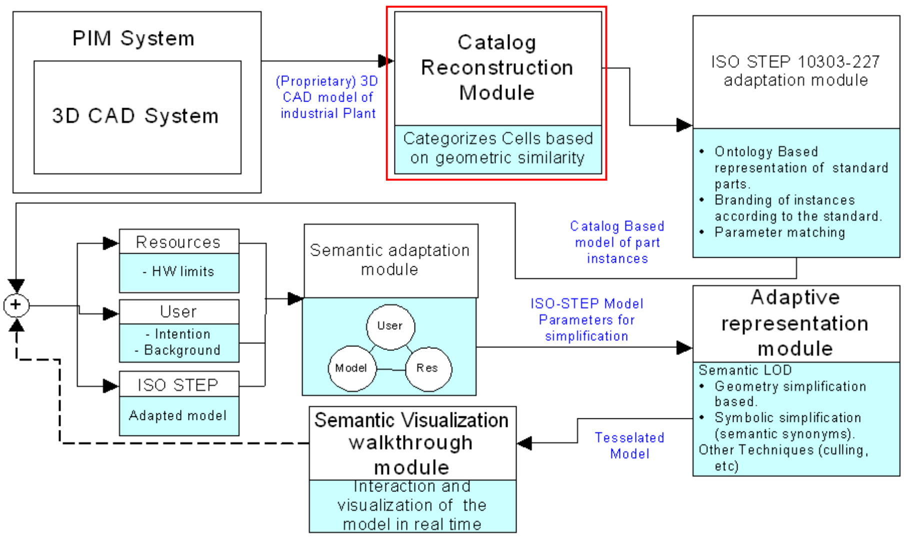


Figure 31. The Catalog Reconstruction Module role in the architecture – First module in the process

As previously described, a parts catalog is used to store the information about repeated instances of parts in the CAD model and to set up a relation between the elements and their semantic class. This catalog has to be semi-automatically reconstructed using structural information of the CAD model and the knowledge of the user.

5.1.1 Searching and classifying instances

General methods for searching repeating structures in unorganized sets of geometric primitives exist, but they are usually slow on large models [SBM01]. The estimated runtime for the models studied in this work may easily exceed a full day in that approach. Also, the focus of this research is the compression of models, not the adaptation for visualization purposes.

There is an emerging research area which will be quite applicable in the future to this module of the methodology: *Shape Similarity Detection*. In this line, an excellent reference for up-to-date methods to compare shape similarity on 3D objects is found in [ANMO05]. The objective of these methods is to investigate how shape similarity algorithms can be used to extract, formalize and associate semantics to shape in specific context (such as engineering design, styling, virtual reality, manufacturing), automatic search and comparison of 3D objects coming from 3D CAD models, FEM datasets, etc.

To mention some of the most closely related works to this research, I can point to the shape similarity algorithms (based on alpha-shapes and other structures) of Ohbuchi, [OHMI05], based on the previous work of Osada, which are tolerant to topological geometrical errors and degeneracy. This work is very similar in spirit to my research, since it deals with *oriented point sets* where distance and orientations are statistically compared for shape similarity. This is however a more ambitious (and complex) approach; as explained below, I have implemented a more simple instance matching algorithm as a proof of concept of the validity of the methodology , which works well (in simplified conditions) and is fast for the purposes of this research.

Other interesting approaches are the 3D graph-like descriptors of Biasotti and Marini,[BIMA05] which decompose the shape into relevant subparts; and the work of Pratt and Srinivasan [ANMO05] which also relates ISO-STEP 10303 with parametric feature representations for shape similarity.

I have focused on a fast algorithm for finding ***instances*** (repeated cells no matter their orientation or position in space not sorted, as in a soup of elements), which is a reasonable approach since the engineering parts rarely correspond to exactly one geometric primitive. The real-world models I have studied from different systems preserve this grouping structure. No assumption is made regarding the internal order of the primitives inside a cell.

This is a reasonable approach since the original CAD model was usually assembled using parts catalogs and the cell boundaries are usually preserved. Even though this method will not locate repeated elements that are not organized in cells, as is possible with the more sophisticated methods described by [ANMO05], it is still a sufficient approach. The runtime advantage compensates for the possible loss and the near-real-time character of this work is preserved.

In a first phase of the catalog reconstruction algorithm, repeating cells from the model are added to the catalog. In a second phase -after adding the new cells to the catalog – the module tries to make a prediction of the part classes based on the geometric elements of the templates. This prediction will produce a certain amount of errors that must be corrected manually by the user (thus introducing a semi-automatic component).

5.1.2 The Cell Matching Concept

For the initial, automatic classification of instances an algorithm is needed that decides whether two cells Ci and Cj **match** each other, this is:

Ci and Cj ***match*** *if Cj can be considered as a spatial instance of Ci.*

In Figure 32 different spatial instances of the same object are shown. It is important to notice that the 3D CAD model does **not** contain explicit information about this instancing (this is the most general case, especially if the integration in PIM systems is not available in the 3D CAD Industrial Plant model)

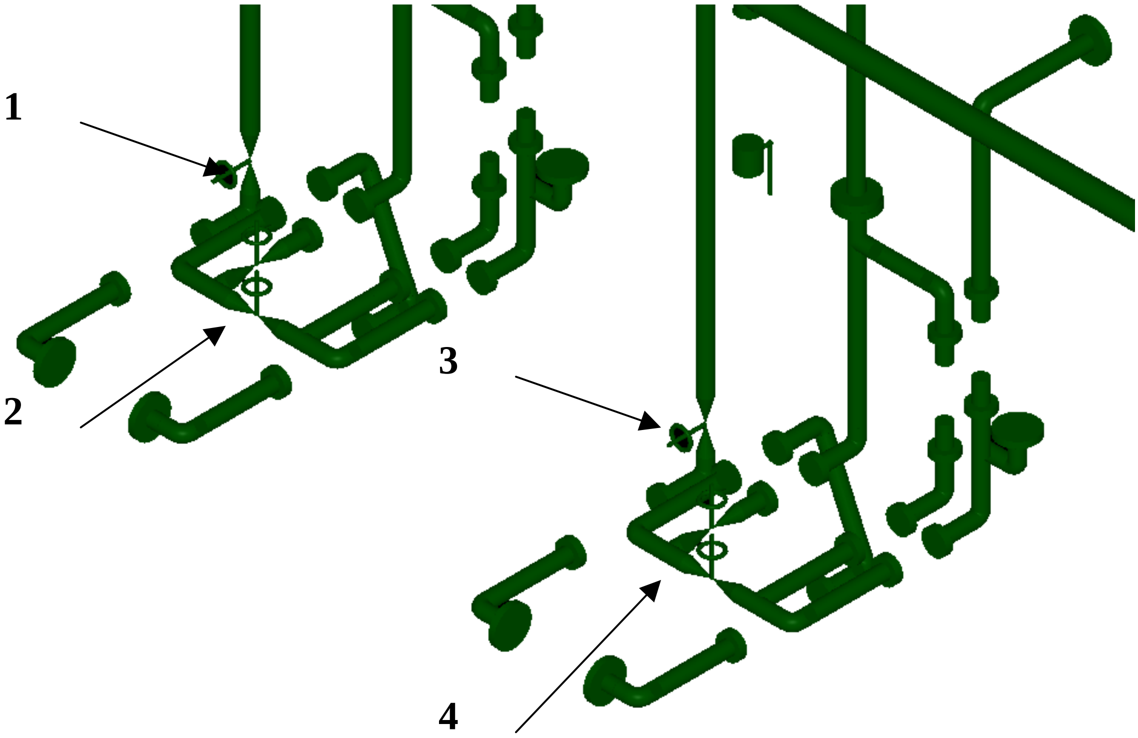


Figure 32. Sample of non-explicit instances in the 3D CAD model: 1,2,3 and 4 are **spatial instances** of the same valve, and **match** each other

In a real world model, several thousands of cells will be matched against each other in the catalogue reconstruction module. To preserve the near real-time nature of my approach, one important requirement for the algorithm is to be fast.

The quality of the matching algorithm can be defined through the number of templates produced from a given set of cells. Too few templates mean that cells with significant differences are merged together. Too many templates mean the user's effort for manually correcting the catalog will rise and also the time that is needed for matching a cell against all templates in the catalog during the conversion phase increases.

The first approach was to match two cells solely based on the cell's topology. The cell topologies of both cells were traversed recursively and the geometric primitives were compared one-by-one. A difference in their topological structure or geometric primitives was interpreted as a do-not-match result. This approach proved to be very fast, but not feasible, since visually identical elements often had variations in their cell structure – especially if the cells of both example models were considered.

5.1.3 Topology based matching

I considered a first approach matching two cells solely based on the cell's topology. The cell topologies of both cells were traversed recursively and the geometric primitives were compared one-by-one. A difference in their topological structure or the kind of geometric primitives was interpreted as a do-not-match result. Only if the topology matching was successful, a more detailed geometric matching was performed. This approach proved to be very fast, but not feasible, since visually identical elements often had variations in their cell structure. Furthermore, I had an initial assumption that proved to be wrong: that cells were stored in a normalized orientation – since they originally came from a catalogue – and were then positioned in the model using a transformation matrix. Instead, the cell's geometry is often relocated by direct redefinition of the parameters of the geometric primitives.

The basic pseudo-algorithm for this approach is illustrated in Figure 33. In case it can be *guaranteed* that the internal topological structure is preserved between spatial instances, this algorithm could be used, since it is also faster that other algorithms. However, this is not the general case, and the *point-clouds based matching* algorithm (explained in the next section) has a more generic nature.

To calculate the involved transformation of the pseudo algorithm, I developed a simple algorithm that is in some parts similar to the algorithm described by Shikhare for matching components [SBM01]. However, I do not use the Hostelling Transformation to compute a normalized orientation. Instead we assume – considering that the cells originally came from catalogues – that the structure of the two cells is similar. Thus, we use the first three points from the beginning of the geometric description to calculate a transformation that transforms the elements into each other. Then the two elements are compared using a fuzzy method similar to Shikhare's method.

During the first stage of the algorithm the cell is converted into two lists: a list P of points in 3D space and a list S of scalar parameters. We call the tuple (P,S) a cloud and the resulting space a cloud space. Each primitive of the cell contributes to the cloud with a number of points and the exact same number of scalar values, as shown in Table 6. We rely on the assumption that the **topology matching holds,** thus we look for the 4 first non-coplanar points of each cell (where no 3 points are collinear) as basis for the calculation of T.

Table 6. Example Contribution of Primitives to calculate T

Primitive	#	Point List	Scalar List
Cone	2	TopCenter, BottomCenter	TopRadius, BottomRadius
Arc	3	Center, Start, End	Primary, Secondary, Sweep
Ellipse	2	Center, Center	Primary, Secondary
Line, Shape	n	All boundary points	n*(0.0)

Two clouds $C_1 = (P,S)$ and $C_2 = (Q,T)$ are defined as ***matching*** in this context if:

1. P and S contain the same number m of elements, and the elements are of the same type.
2. A one-to-one non-scaling affine transformation T exists that maps the 4 non-coplanar points P and Q into each other.
3. The elements of the two scalar clouds S and P are equal with respect to the one-to-one mapping T.

Thus, T is calculated in the standard way of mapping a coordinate system into another, since the 4 non coplanar points in each cloud define vectors that serve as a basis for 3D space. This is actually a *map of a linear space to another linear space* where the basis B_p and B_q for the 3-dimension linear space are defined as differences between the 4 non coplanar points.

```
boolean MatchCellsTopology (cellA, cellB)

if cellA.countPrimitives() == cellA.countPrimitives()

//check all primitive types first
    for i=0 to (cellA.countPrimitives()-1)
      if  (cellA.getPrimitive(i).type()  !=
           cellA.getPrimitive(b).type())
                return false
    next i

// Find a possible transformation cellA->cellB based
// on the first geometric primitive in both cells
    firstPrimCellA = cellA.getPrimitive(0);
    firstPrimCellB = cellB.getPrimitive(0);
    T = GetTransformationMatrix(firstPrimCellB, firstPrimCellA)

//check correspondance of all primitives
//both geometry location/orientation
//and attributes (color, design layer, etc.)
    for i=0 to (cellA.countPrimitives()-1)
        transfCellB = cellB.getPrimitive(i).copy()
        transfCellB.transform(T)
        if  ( (cellA.getPrimitive(i).position()  !=
                         transfCellB.position() ) and
              (cellA.getPrimitive(i).orientation()  !=
                         transfCellB.orientation() ) and
              (cellA.getPrimitive(i).attributes ()  !=
                         transfCellB.attributes() ) )
            return false
    next i

    return true;
else
    return false
```

Figure 33. Pseudo-algorithm for topology based matching

5.1.4 Point-clouds based matching

There are several methods proposed in the literature to match point clouds representing 3D surfaces **(**[CHV02]**,** [GRU05]**)**, since the problem of registration of point clouds is very relevant in several fields (3D model acquisition, reverse engineering, quality control, etc.).

Some of the most popular algorithms are the Iterative Closest Point (ICP) algorithm [CHV02], with several variations, the Least Square Surface Matching (LS3D) method [GRU05], and the Iterative Closest Points using Invariant Features (ICPIF) [SHA02]. Also the mentioned approaches at the beginning of these section, albeit from a different nature (shape similarity analysis) are very relevant in this sense.

I have considered the possibility to apply some of these algorithms to the cell matching problem, generating point sets from the cells. In the generic registration problem *the correspondences between the point sets are unknown a priori* [CHV02] and no one-to-one matching between the clouds points can be assumed (since they come usually from scanners).

In my case, however, given the special conditions of the models, **this one-to-one correspondence exists**, making the task easier. Thus, I developed a simplified algorithm (somehow similar in the approach to ICPIF, although much simpler and restricted) that could be applied successfully for the cell matching and classification. Again, it is important to recall that the *problem* itself and the need of the Catalog Reconstruction Module are generic; the presented algorithm is indeed one solution but not the only possible one.

5.1.5 The Cell matching algorithm

The cell matching algorithm is based in the fact that we don't know more information than the geometric data (in other words the spatial components of each feature in the model). From a generic point of view, the problem we are solving is to determine if two complex CAD objects are equivalent (if there is a rigid transformation that is able to transform one cloud into the other).

We can reformulate the cell-matching problem as follows:

> *Given two cells* C_i *and* C_j*, each composed by an unordered set of geometric primitives,* C_j <u>*matches*</u> *or* <u>*is an instance of*</u> C_i *if a rigid body transformation matrix* T *exists that transforms* C_j *into* C_i *.*

The cell-matching algorithm must:

(i) Decide if C_j *matches* C_i *within a given tolerance.*
(ii) Obtain the transformation matrix T*.*

We will give some basic definitions for the algorithm below.

A *cell* C_i is composed by an unordered set of *geometric primitives* G_{Cij}:

$$C_i = \{ G_{Ci1}, G_{Ci2}, \dots , G_{Cim})$$

Each G is characterised by:

1) A *characteristic point set* CPS_G *:*

A set of points associated *univocally* with the *spatial position* of G. Notice that CPS is not an exhaustive set of surface points (as to differentiate this from ICPIF algorithms)

2) A *characteristic scalar set* CSS_G :

A set of scalar values associated *univocally* with the *dimensions* of G.

3) A *characteristic type* CT_G

This is a code correlative with the geometric primitive type.

CPS_{Ci}, CSS_{Ci}, CT_{Ci} are the sets formed with the CPS, CSS and CT of all primitives G_{Ci}.

For example:

$$\begin{aligned} CPS_{cyl} &= \{P_{origin}, P_{end}\} \\ CSS_{cyl} &= \{r\} \\ CT_{cyl} &= \{CYL\} \end{aligned}$$

Where the points are the centres of the covers, r the radius and CYL the type of the cylinder primitive. Notice that CPS varies between instances of the same cell but CSS and CT don't.

The *point cloud* PC_{Ci} is the point cloud formed by all the CPS of the primitives G_{Ci}. Each CPS*-point* keeps a link with its corresponding CSS and CT.

$$PC_{Ci}=\{CPS_{G1(P0)}, \dots, CPS_{G1(Pn)}, CPS_{G2(P0)}, \dots, CPS_{Gn(Pm)}\}$$

The *ordered point cloud* OPC_{Ci} is the ordered set of all points in PC_{Ci} with respect to the squared Euclidean distance d^2_i from each point to the *barycenter* (geometric centroid) of PC_{Ci}.

$$OPC_{Ci} = \{\{CPS_{Ga(Pb)}, d^2_{ab}\}, \{CPS_{Gc(Pd)}, d^2_{cd}\}, \{CPS_{Ge(Pf)}, d^2_{ef}\}\}$$

With $d^2_{ab} \leq d^2_{cd} \leq d^2_{ef}$

The matching algorithm

The core of the matching algorithm is based on the geometric comparison between PC_{Ci} and PC_{Cj} as follows (if C_i and C_j have both n geometric primitives):

Step 1-. Discard obvious non-matching cells (different count of primitive types CT).

Step 2-. Get OPC_{Ci} and OPC_{Cj} ordered with respect to the distance of each point to the respective barycentre.

It is known from the traditional physics that the centroid of a set of ***k*** points masses m_i located at positions x_i is:

$$\overline{X} = \frac{\sum_{i=1}^{k} m_i \cdot x_i}{\sum_{i=1}^{k} m_i}$$

This, if all masses are equal simplifies to:

$$\overline{X} = \frac{\sum_{i=1}^{k} x_i}{n}$$

which is the ***barycenter*** definition we use for our calculations.

Step 3-. Check that the ordered vector V_{di} with these distances in OPC_{Ci} is equal within a given tolerance to the corresponding ordered vector V_{dj} of distances in OPC_{Cj}. If not, C_i and C_j don't match.

Step 4-. Compare also the respective CSS_{Ci} and CSS_{Cj} (following the order given by V_{di}). If not equal, it means that although the point clouds coincide, the invariant scalar values don't; therefore C_i and C_j don't match.

Step 5-. Get 3 non-collinear points P_{i1}, P_{i2}, P_{i3}, that have unique values of squared Euclidean distance to the barycenter, this is, no other points in OPC_{Ci} have the same distance to the barycenter. As OPC_{Ci} is already ordered by this distance, this is fast.

Step 6-. Get the corresponding 3 points P_{j1}, P_{j2}, P_{j3} in OPC_{Cj} such that:

$$d^2_{j1} = d^2_{i1}$$
$$d^2_{j2} = d^2_{i2}$$
$$d^2_{j3} = d^2_{i3}.$$

As OPC_{Cj} is ordered too, this is straightforward.

Step 7-. Calculate the rigid transformation T that transforms P_{j1}, P_{j2}, P_{j3} into P_{i1}, P_{i2}, P_{i3}. If T exists,

C_i and C_j match.

In the rare case that the 3 points of step (5) cannot be obtained, a more general algorithm (e.g. ICP) could be executed. Typical clouds coming from the CAD models studied contain typically less than 100 points. The models have also several thousands cells, classified in tenths to hundredths of groups. In the practice I have always been able to get these points.

The metric defined by the algorithm is invariant against position, color, orientation and structural cell-organization of the two elements. A matching tolerance of 1% between the points is applied, because several parts showed slight differences in the primitive's position.

The worst case complexity of the function MatchCells is $O(n^2)$ where n is the number of elements in the cell. In practice, however, the function returns usually either immediately because the cloud size of both cells is different, or the complexity is $O(n)$ because the order of the points in both clouds is the same.

5.2 THE ISO-STEP 10303 ADAPTATION MODULE

I present in this section the *Semantic Adaptation Module* of the system. A more detailed explanation about the role of STEP and Ontologies in this work can be seen in chapter 3. Here I just recall some of the basic concepts involved and focus more on the connection of this module with other modules in the architecture.

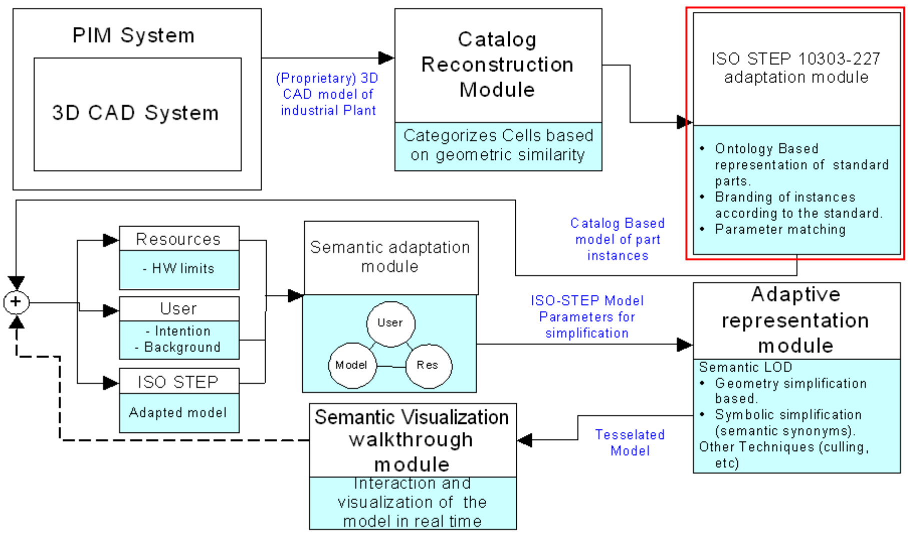


Figure 34. The ISO-STEP 10303 Adaptation Module in the general architecture – second module

A 3D model of an Industrial Plant typically has representations of some pre-defined engineering parts, although tessellated in different ways. These elements are described by an ISO standard (STEP-10303-227 [ISO01]) in the domain of Plant Design, and the adaptation module is in charge of associating the 3D representation with a category of the standard.

5.2.1 The ISO STEP 10303-227 Standard

ISO STEP-10303-227 [ISO01] is part of an international Standard for the computer interpretable representation and exchange of product data. Product data represents information in formal manner suitable for communication, interpretation, or processing by human beings or computers. The objective of STEP is to provide a neutral mechanism capable of describing product data throughout the life cycle of a product independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving. The core of STEP consists of a collection of conceptual models, which describe the content, and structure of product data items. These data models, also called information models, are formally specified in the modeling language EXPRESS **[8].** The Application protocol 227 describes the specifics for plant spatial configuration (Figure 35 shows an excerpt of the EXPRESS-G diagram showing several plant components such as *elbow* and *flange*)

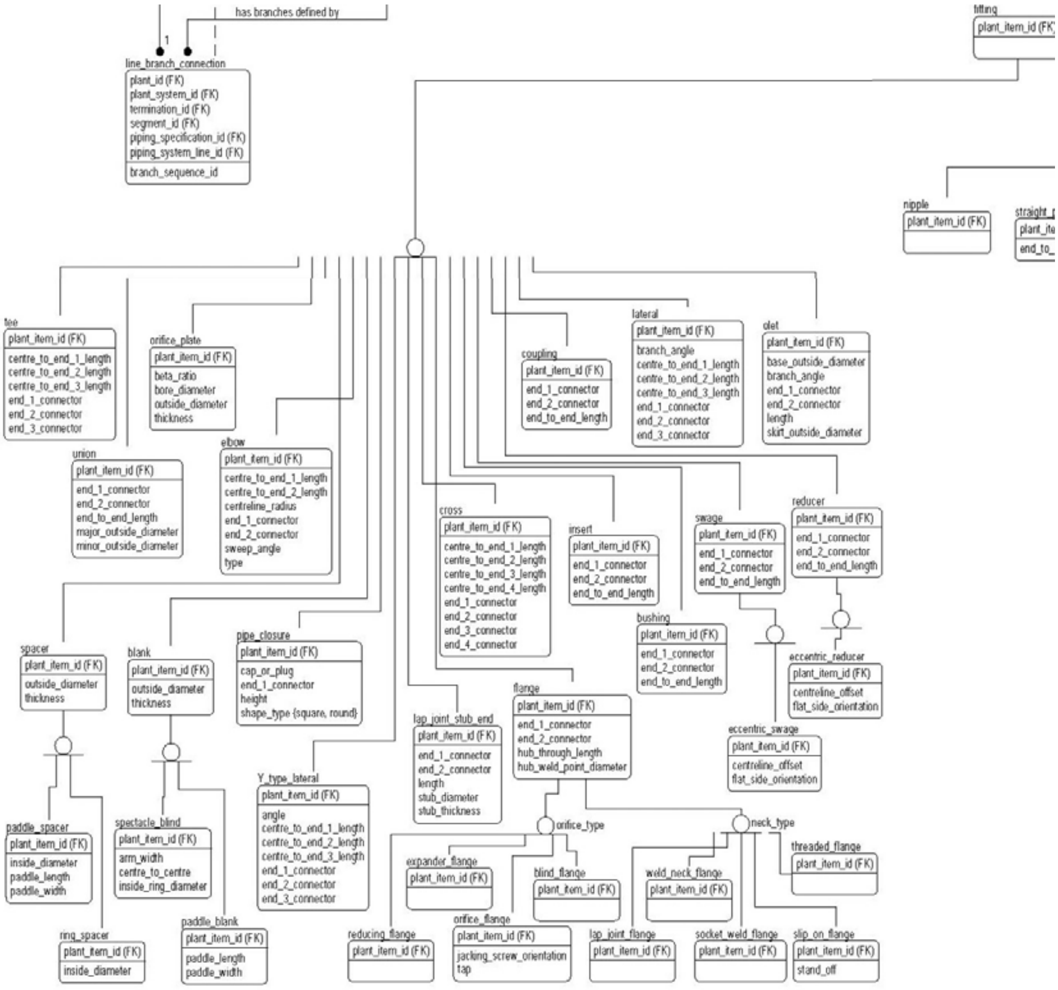


Figure 35. ISO-STEP 10303-AP227 EXPRESS-G Detail – Several Plant Design components are shown.

5.2.2 Motivation for an Ontology Support

I have modeled a domain ontology related to the ISO-STEP 10303 –AP227 standard because our ultimate objective is to have a system where the concepts and relationships of the domain could be modeled and queried using semantic criteria [PLS02], beyond the mere data modeling structures of the standard.

This ontology modeling also allows a more transparent interrogation of the user purpose/profile, which can also be modeled as ontologies. I use ISO-STEP 10303-AP227 as a basis to develop this module.

The main reason to use this approach is related to the fact that STEP is only a data exchange format, but our requirements for semantic simplification required higher capabilities to express relationships and concepts.

5.2.3 Construction of the Ontologies

The ontologies are modeled using Protégé 2000 [PRO04], adapting the classes and relationships (to be more suitable for a knowledge representation model) presented in the ISO STEP-10303-227 [ISO01]**.** This serves as an important contribution to the *model* node of the semantic triangle described in [PTWS05b]. The current ontology of the domain model has a total of **298** classes, **143** slots and **451** frames, and currently represents the **60%** of the ISO application protocol 227.

For the User and Purpose support, I have modelled two ontologies for the *user profile* and for the *user purpose*.

5.2.4 Interaction with the STEP-based Ontology

The model ontology is used by the other modules, and provides the necessary information used to generate the *parameters* for advanced visualization as described in the Chapter 4 (in the mathematical model) .

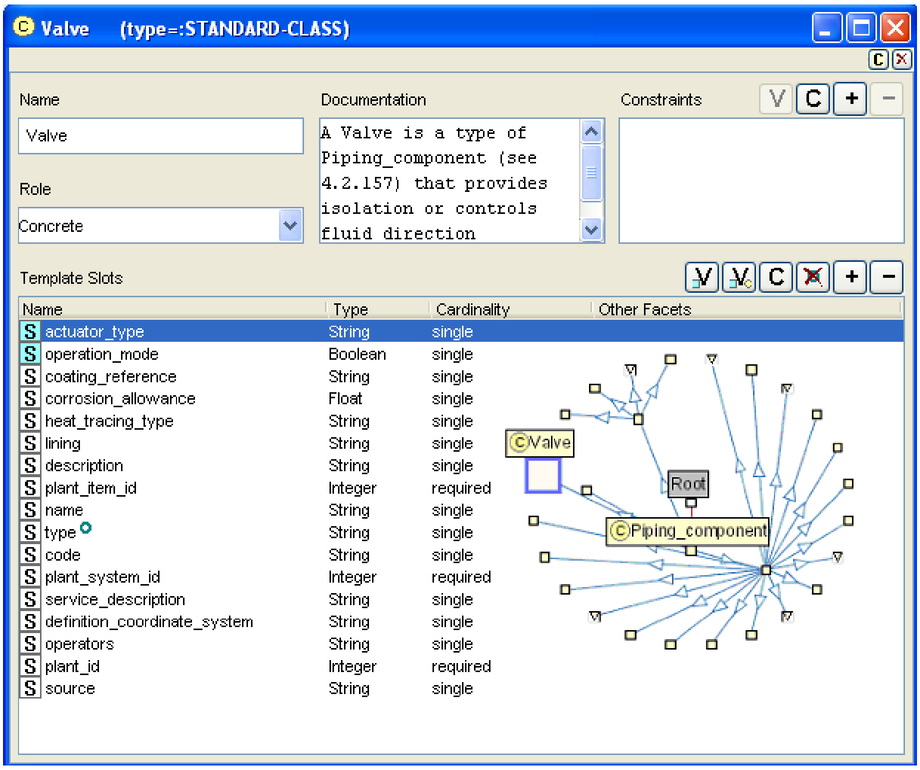


Figure 36. Interaction with the STEP Compliant Ontology – edition and visualization aspects

The Domain Ontology can be explored and queried in different ways, as a support for the user, in case he/she is interested in exploring the concept relationships in the domain. The two mechanisms used are:

- **Exploration of the ontology using the Protégé user interface**

  This mechanism is only useful for people already familiar with Protégé (or any similar tool, including plug-ins such as TGViz, see chapter 3), which is clearly not the general case. This tool should be mainly used by a Knowledge Engineer in the organization, and not by final users of the system

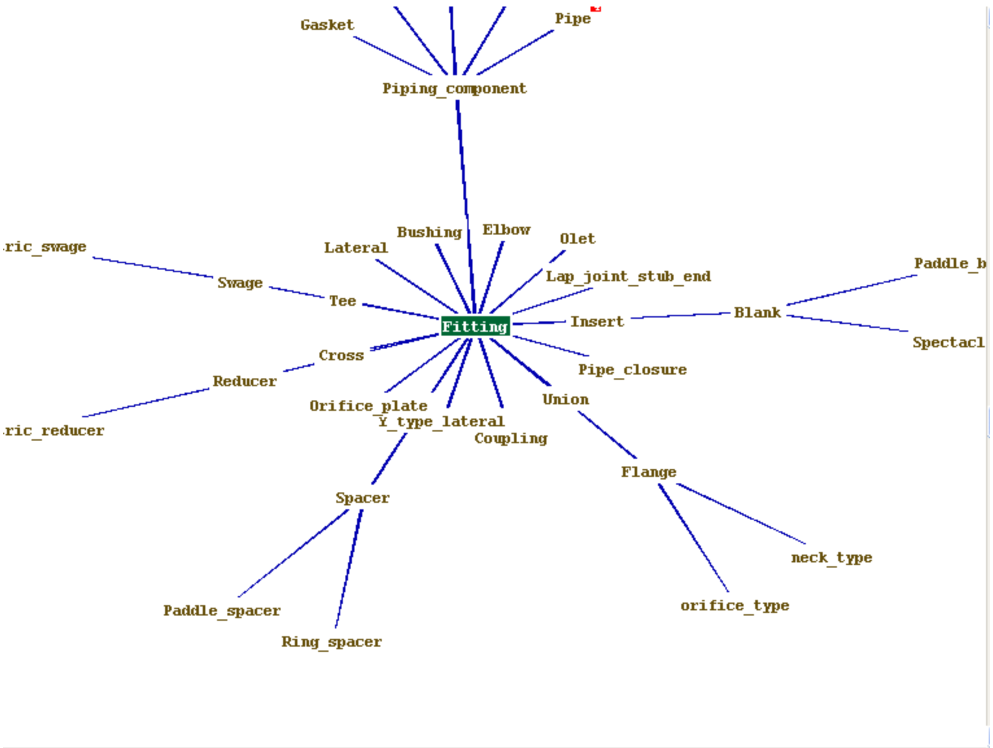


Figure 37. TGviz navigation possibilities in Protégé 2000 for our Industrial Plant Ontology

- **Visual Exploration tool**

  We have done a simple adaptation of a visual exploration tool developed in the cooperative European Project IST-WIDE, where I have participated, in order to navigate through the ontologies of the system. In Figure 38 a screenshot of this tool is shown. Nodes can expand and collapse as desired, and can be put easily in a central position by clicking on them. An advanced pan / zoom / focus functionality allows easy and intuitive navigation of the Domain Ontology.

  The visual exploration tool also allows a direct connection to instances of the model as well as personalization of the vocabulary of the different users –aspects intensively researched in the project WIDE but not the focus of this work.

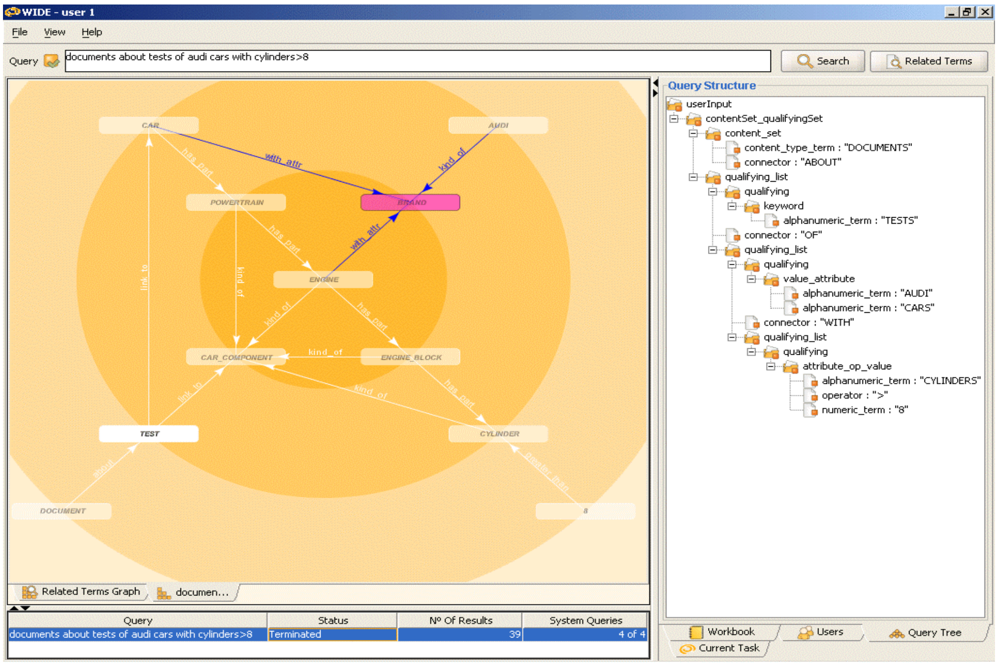


Figure 38. Intuitive exploration tool to navigate through the ontologies. In the figure, the visualization of the graph of concepts related with a query in the IST-WIDE project.

Thus, we do provide exploration possibilities of the Domain Ontology to the users, as a complement to the main objective of the *ISO-STEP 10303-AP227 Adaptation Module*, which is to provide a description based on the STEP standard of the 3D CAD Plant Model (thus *increasing* the explicit semantic level of the model.

In the next step, by specifying

- A *user purpose/profile* (manager, engineer, etc)
- The available *computer resources*
- The 3D *CAD model* itself

we are able to query the system in order to select an optimal adaptive representation of the model (which is done in the next module, Adaptive Representation Module) which is suitable for the walkthrough purposes.

5.2.5 Semantic association of parts with the standard

In order to add the semantic information a two stages approach is followed.

- **Branding:**

Name each group of *cells* (from the previous module) after an ISO – STEP 10303 compliant concept. This process is called "*Branding*". The user visualizes one representative part of the cell group and matches it with a concept of the ontology in a graphical concept tree (see Figure 39).

- **Matching**

Once the cell group is associated with a concept in the ontology domain, the user matches semi-automatically the cell parameters (geometric features) with those parameters specified in the ISO-STEP standard. This process is called "*Matching*".

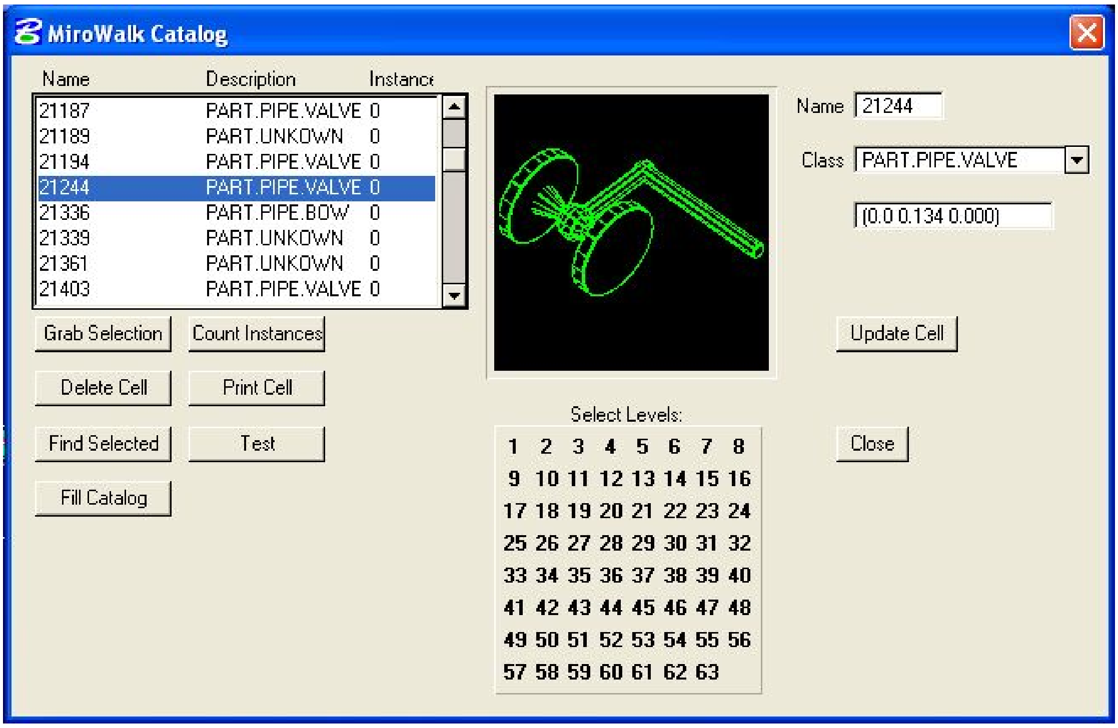


Figure 39. Screenshot of *Cell group* branding – naming of geometric groups according to the Catalog.

Some implementation details on Matching & Branding

The matching & branding tool is implemented as a *MicroStation MDL* plug-in. MicroStation is one of the CAD systems used in this work, since it is a common CAD software under Plant Design software.

Figure 39 shows a screenshot of the matching & branding dialog as it appears within MicroStation. In the top left corner a list of all templates in the catalog is shown. On its right there is a rendered image of the currently selected template. A search through the model for all cells of a model can be triggered by pressing the "Fill Catalog" button. This search can be restricted to certain levels of the model using the "Select Levels" area.

The "Grab Selection" button will add all cells currently selected in the model to the catalog. The "Name" and the "Class" text-field on the right side of the dialog allow a manual correction of the cell class. Additionally, cells can be deleted, the tool can count the instances of a selected template in the model, and the structure of a template can be printed to the log file for debugging purposes.

MicroStation already has a built-in cell library that contains template cells that can be inserted into the CAD model. This cell library can be accessed using the MDL API. I use this functionality as a base for implementing our catalog. This has two advantages: on the one hand, no extra solution for persistent storage of the catalog has to be implemented. On the other hand, the catalog can still be accessed by the CAD user using MicroStation tools, since it is data-wise a normal Micro Station cell library. Also existent cell libraries can be directly used as a MiroWalk parts branding & matching.

To add cells to the catalog and to match cells from the model to catalog, templates the catalog module described in the next sub-chapter is used. Basically, the catalog tool is the user's front-end for the branding & matching module.

5.3 THE SEMANTIC ADAPTATION MODULE

This module takes as input the adapted 3D CAD model in which the families of cells identified in the Catalog Reconstruction module already correspond to ISO-STEP 10303-227 parts. However, this is only one of the aspects I consider in order to make a good semantic compression of the model for a Design Review walkthrough scenario.

As explained in **(**[PLS02] [PWTS04a] [PTWS05b]**)**, I have defined a framework in which three factors influence the final adaptation of a 3D CAD model for Design Review walkthroughs:

(i) *The user intention and background*,
(ii) *The available resources*, and
(iii) *The model characteristics*

In many walkthrough applications, there is very little or no consideration of the profile and motivation of the user of the system. I introduce explicitly the concepts of :

- *User profile,* and
- *User purpose*, which influence the final output model in this semantic adaptation module.

Thus, the parameters used by different Computer Graphics techniques (such as LOD, culling, etc.) inside the *Adaptive Representation module* are defined (with a rule-based approach) according to the user needs.

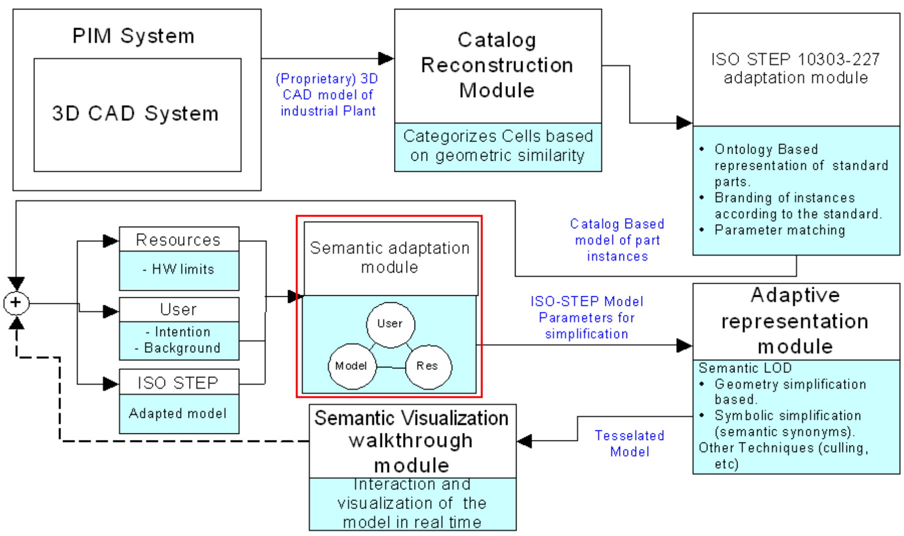


Figure 40. The Semantic Adaptation Module – Third module in the general architecture

In a similar way I take into considerations the *available resources* (e.g. clusters of PCs vs. single PC, available RAM, etc.) to prepare the walkthrough experience, creating different adapted representations in each case. For example, in Figure 41, the upper part depicts an ISO-STEP section of a piping component that already includes the model semantics, in the sense that the model is based on cell families of parts with ISO-STEP parameters.

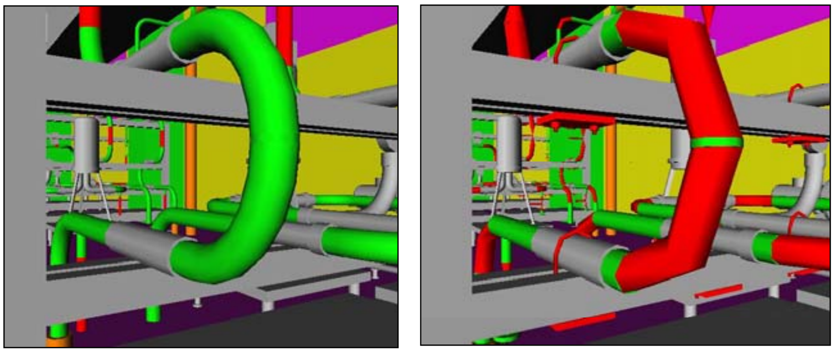


Figure 41. Semantic adaptation of graphical representation, left image is not simplified, right image is simplified for specific conditions.

The user and resources can however influence further the final walkthrough experience: in the picture the profile *piping engineer* and the purpose *piping fixation* forces the system to keep the small clamps and simplifies the elbows, whereas in the right picture the profile *manager* and the purpose *presentation to customers* applies a drop culling technique to the clamps and shows the elbows in geometric detail.

We are now moving from the rule-based adaptation system of *user profile* and *available resources* towards a deeper integration with the *model characteristics,* by modeling those two aspects in special ontologies that can be integrated with the model ontology for better inference of the right parameters and techniques to use.

5.3.1 Some Comments about the Ontology Processing Modules

The ontology module contains all functionality related to decisions based on semantic criteria. Prior to using this module the *semantic context* must be selected by calling a function to specify a user, a resource, and a model. Using this information the module makes semantic decisions regarding the export process based on semantic rules.

The ontology module sets – based on semantic criteria – all parameters needed for the conversion process (e.g. the global tessellation complexity parameter) – work that previously had to be done manually by the user. The module also decides which techniques to apply to a particular part of a particular class. The logic for the semantic decisions is encoded in a set of **semantic rules**, for which the calculation of *fges* and *fsem* play an important role.

The currently implemented set of semantic rules is not very extensive but it is enough to effectively prepare an adapted representation of the 3D CAD model for visualization purposes.

5.3.1.1 The Calculation of *fges* and *fsem* Factors

As stated in the Mathematical Model chapter, one of the most important roles of the *Semantic Adaptation Module* is:

> The calculation of the *Functional Semantic Factor* (*fsem*) and the *Geometric Aesthetic Factor* (*fges*) for each candidate technique for tessellation of parts.

The details of the influence of these factors in the visualization system are explained in the Mathematical Model chapter, but it is important to emphasize in this section that both are calculated on the basis of the *user, purpose, resources,* and *model* ontologies. These separate ontologies will be described in next section.

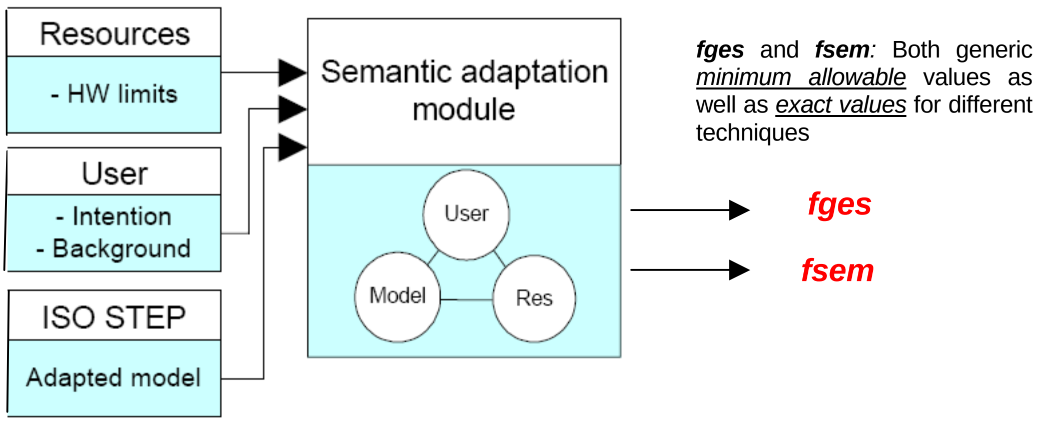


Figure 42. *fges* and *fsem* as output parameters from the Semantic Adaptation Module

Let's recall that the value of *fges* quantifies the subjective *quality of the geometric aesthetic perception* of a 3D representation of a *cell* independently from the functional / semantic value (0.0 is lowest, 1.0 is highest).

In a similar way, let's recall that the value of *fsem* quantifies the subjective effectiveness of the 3D graphical representation of a *cell* c_i in a walkthrough to convey the *functional and semantic role* of that representation for a specific user purpose and profile (0.0 is lowest, 1.0 is highest).

Both values are very useful and needed in the formulation of the mathematical optimization problem (see Chapter 4)

5.3.2 Some Generic Aspects of the Mirowalk Ontologies

In the next chapter a detailed description of the domain ontology in our system (the Domain Ontology for Industrial Plant Design) is given. Clearly, in the *semantic triangle* concept, this ontology plays a central role related with the **model** node of the triangle.

However, there are other ontologies in the system that serve as support for the semantic aspects related to the *user* (*profile* and *purpose*), the *resources,* and the *techniques used.*

Mirowalk has **5 interrelated ontologies** (including the Domain ontology already described) that allow the support of the semantic visualization of large plant models. Thus, in this section I will describe some of the different aspects related to the edition, storage and interrogation mechanisms on those ontologies in general, as well as to give a brief description of the each one.

5.3.2.1 Ontologies Languages in Mirowalk

In general, the Mirowalk system uses the **OWL (Ontology Web Language)** [OWL04] to edit the ontologies. This decision was made up recently, once the OWL tools allowed the edition and storage of OWL Ontologies without assuming too many risks.

OWL is a W3C Recommendation since February 2004 and, quoting their promoters, it has been designed for use by applications that need to process the content of information instead of just presenting information to humans. OWL facilitates greater machine interpretability of Web content than that supported by XML, RDF, and RDF Schema (RDF-S) by providing additional vocabulary along with a formal semantics. OWL has three increasingly-expressive sublanguages: OWL Lite, OWL DL, and OWL Full.

5.3.2.2 Mirowalk Ontologies Edition

The Edition of the Mirowalk Ontologies has been performed with the Ontology Editor **Protegé 2000** [PRO04]. The main characteristics of Protégé is that its community of users is composed of thousands of people, it is open-source, multiplatform (Java) and is able to provide an extensible architecture for the creation of customized knowledge-based applications.

5.3.3 The System Ontologies for Mirowalk

A short presentation of the 5 system ontologies is given in this chapter.

5.3.3.1 The Domain Ontology

This ontology is directly related with the *model* node of the Semantic Triangle. Its role is to model the most important concepts for the domain of Industrial Plant Design, based on the ISO-STEP 10303-AP227 standard. As explained in that chapter, this ontology has a different focus than the Plant Ontology developed in the Osaka University of Japan (by the group of Mizoguchi[MKS00]), since our goal is mainly focused on visualization aspects.

This is indeed the ontology that allows an identification and semantic enhancement of the 3D CAD model so that it can be converted and visualized in VR following not only geometric but also semantic considerations. Figure 43 shows 2 screenshots (one of Protégé and one of TGVIZ) of the Domain Ontology.

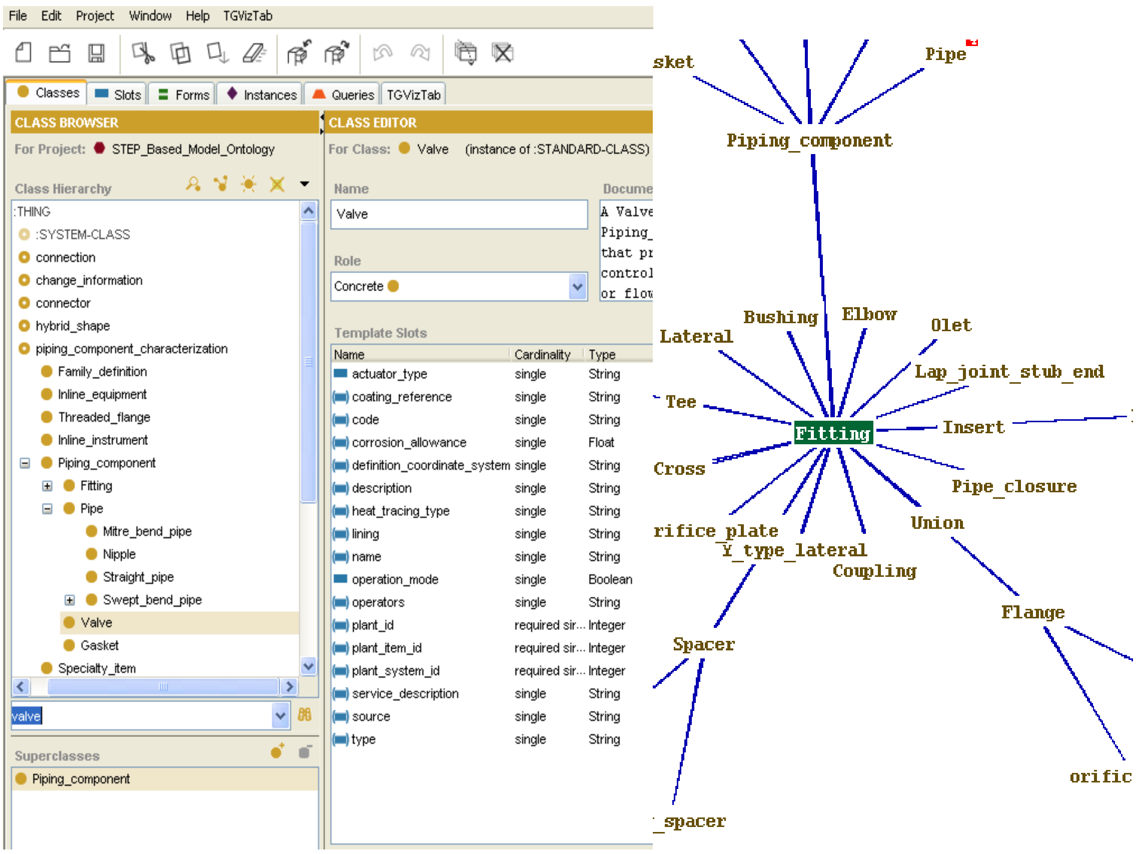


Figure 43. Screenshot of the Domain Ontology – Visualization with Protégé 2000 and with TGViz

5.3.3.2 The Visualization Purpose Ontology

I have also modeled a *Purpose Ontology* that includes some of the most typical purposes involved in visualization of large plant models. This purposes influence decisively the way in which the visualization should be produced.

The work of Mizoguchi [MIK00], from the Osaka University, also points out that a purpose ontology is needed as a complement to the domain ontology in the Plant Design area. I follow a different approach since his task ontologies are mainly *operational*, (i.e. monitor, diagnose, operate, enumerate, predict, etc.), this is, focused on the functional aspects of the industrial plant as a system, whereas our *purpose ontology* is focused on tasks related with mainly with the visualization. However, there is no fundamental difficulty in considering a potential merge between our purpose ontology in the visualization aspects and his ontology in the operational aspects.

In the EU Project IST-WIDE, we have developed mechanisms to define, edit, query and relate the task ontologies (for car design) with the *user* ontologies [SPO04]. I use a similar approach in our framework to relate purposes and users. Thus:

- A *purpose* is linked with one or more *user profiles*
- A *purpose* is linked with several recommended *resources*
- A *purpose* is linked with several relevant concepts of the *Domain Ontology*
- Thus, the relationships *user-model-resources* are exploited to calculate the best parameters for the technologies used in the semantic visualization module.

In Figure 44 I show some of the classes of the *purpose ontology* for our framework.

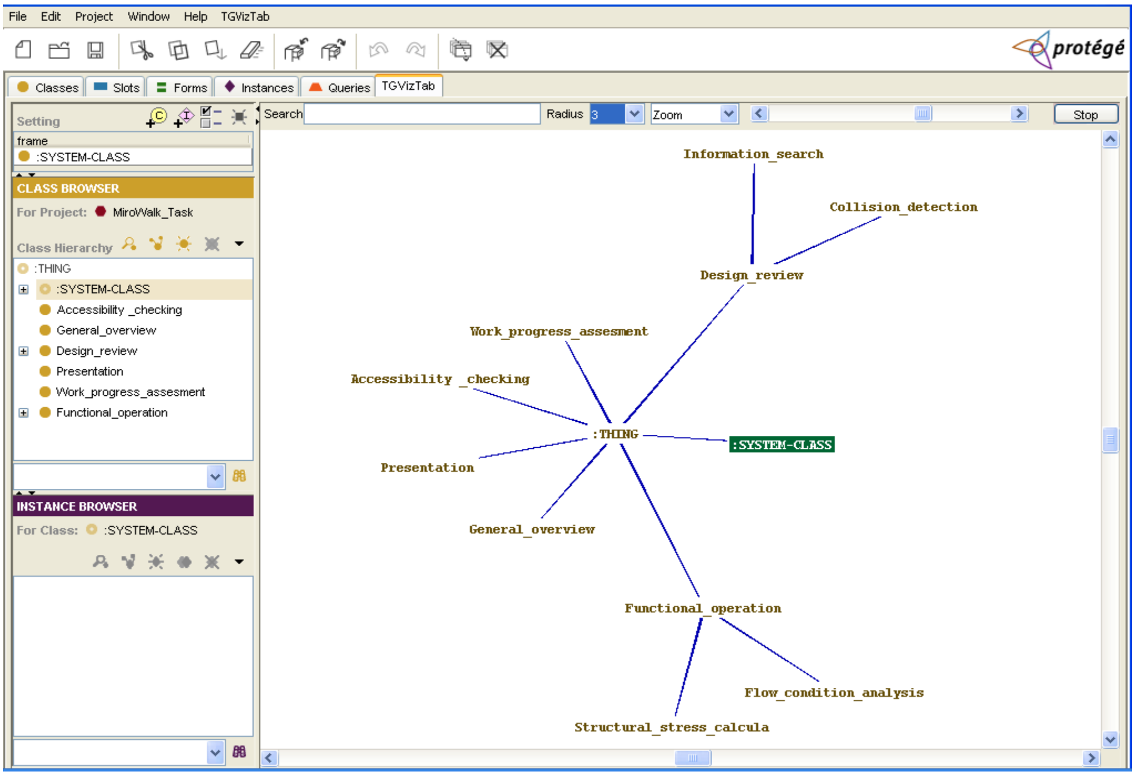


Figure 44. A part of the visualization purpose ontology in the Mirowalk framework - TGViz screenshot

5.3.3.3 The Resources Ontology

Another important aspect of the system is the consideration of the *available resources* as a critical factor to adapt a visualization experience oriented to a specific user. Thus, I have modelled a simplified prototype of a *Resource Ontology*, which covers some of the most relevant aspects to consider in this regard (e.g. available memory, CPU speed, etc.).

The mathematical model already takes this into account in the form of restrictions to the integer programming problem. The classes of this ontology have slots related to those restrictions (e.g. for a specific PC it would specify the available RAM). In Figure 45 a screenshot of this ontology is shown.

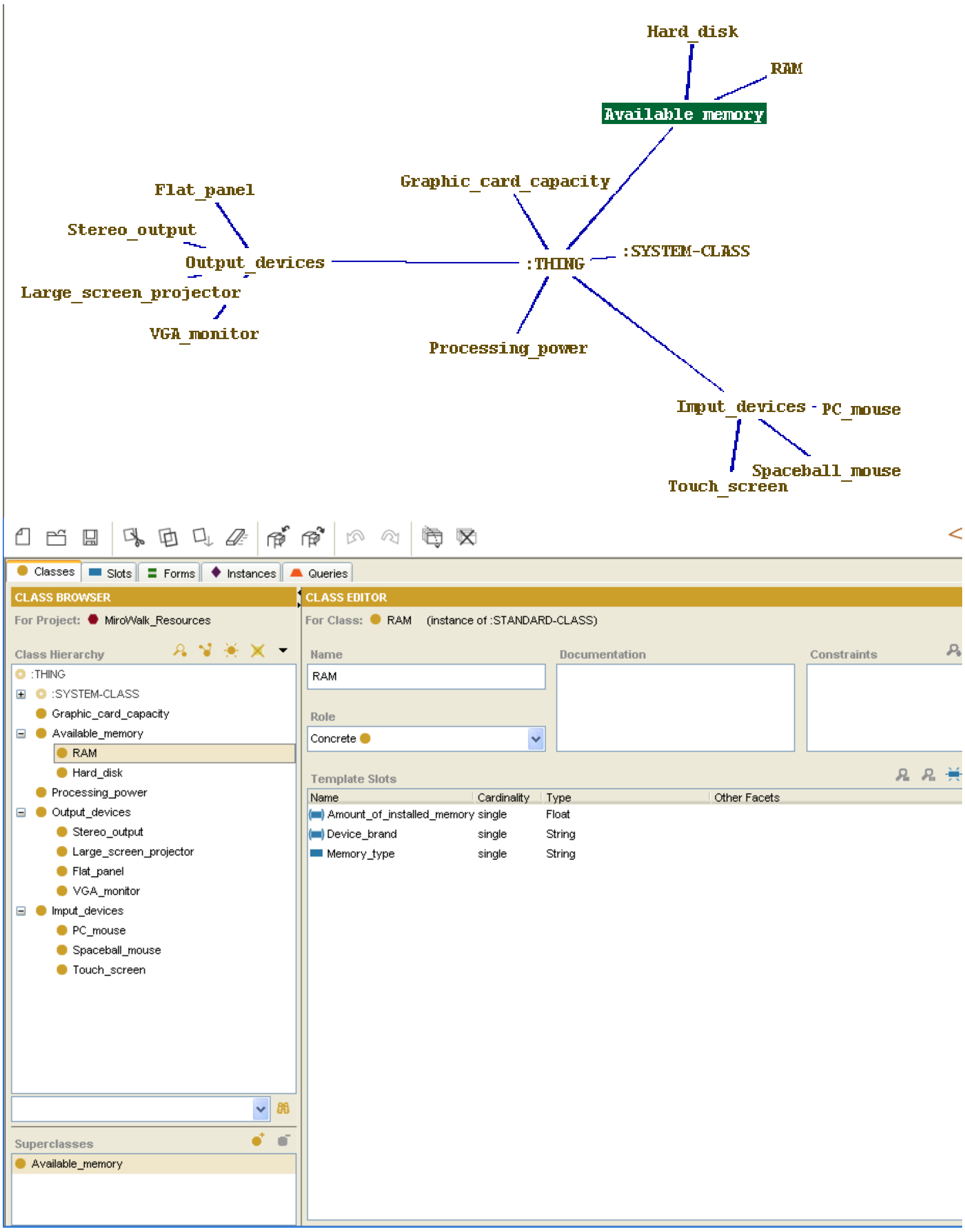


Figure 45. The Resources Ontology – Used for the third node in the Semantic Triangle concept

5.3.3.4 The User Ontology

I have modeled a *user ontology* that reflects mainly the role of the user in the system, taking into account his background and interests, as well as relating this profile with the *user intention,* which is reflected in the defined purpose. This is indeed of the fundamental considerations that the semantic visualization framework takes into account in order to prepare a suitable visualization experience: *who* is the user of the visualization, and *what for* is he requiring this functionality. Again, as in the case of the *purpose ontology*, I use a similar internal relationship model as in the European project IST-WIDE, which takes also into account user profile and purpose in order to provide a better navigation and exploration of the ontologies for the purposes of Knowledge Management and Information Sharing.

In Figure 46 I show some of the classes of the *user ontology*. As explained in the mathematical model chapter, this ontology is critical in order to assign adequate values to *fsem* and *fges* (see Figure 42), which are also instrumental in the solution of the internal optimization problem which leads to the selection of specific techniques for the conversion and visualization of the Plant models.

I have grouped the potential users in *technical and non-technical users*, which subcategories for different profiles. This is a major division criteria since the for visualization purposes this acquires a high relevance.

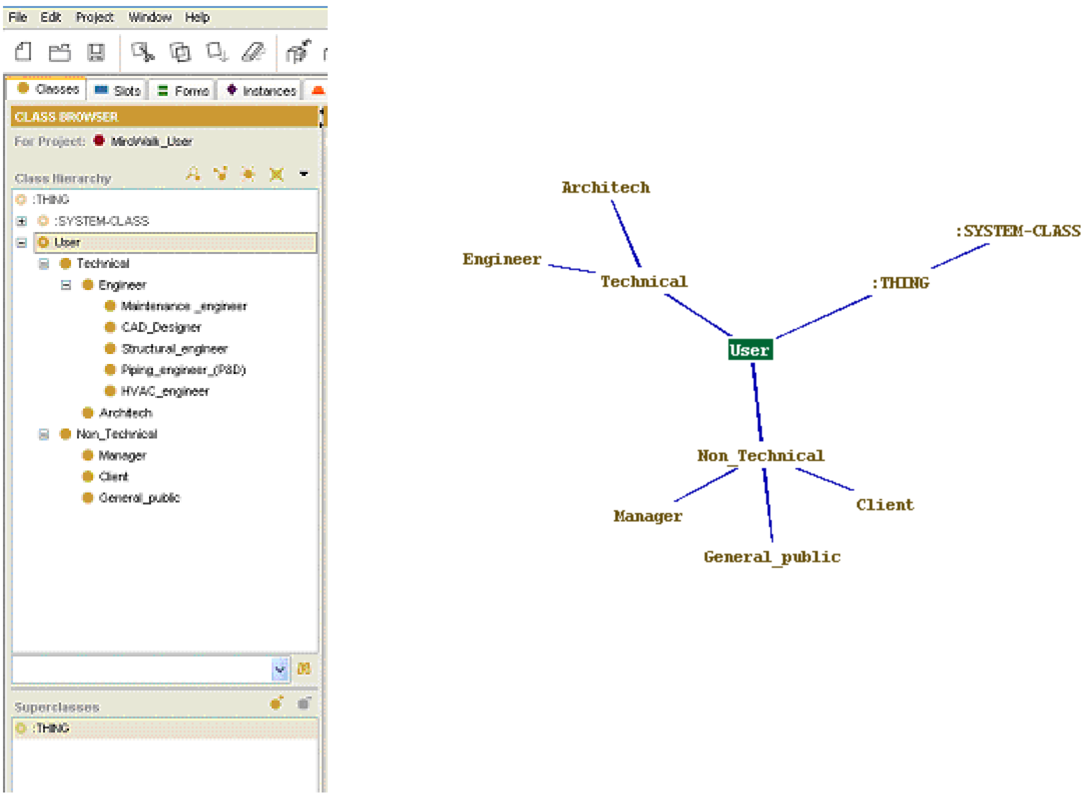


Figure 46. Section of the User Ontology in the Mirowalk System – Technical and NonTechnical users

5.3.3.5 The Techniques Ontology

The chapter 4 explains that the *conversion/tessellation techniques* are critical factor to take into used in the adaptation of a 3D CAD model for visualization purposes. In fact, the appropriate selection of which techniques should be used in a given context is one of the main outcomes of the internal optimization problem given in that chapter. Each technique is evaluated according to its *fsem* and *fges* factors. In Figure 47 a simplified ontology for the techniques used in the system is shown. A detailed explanation of these techniques is given in chapter 5.4.

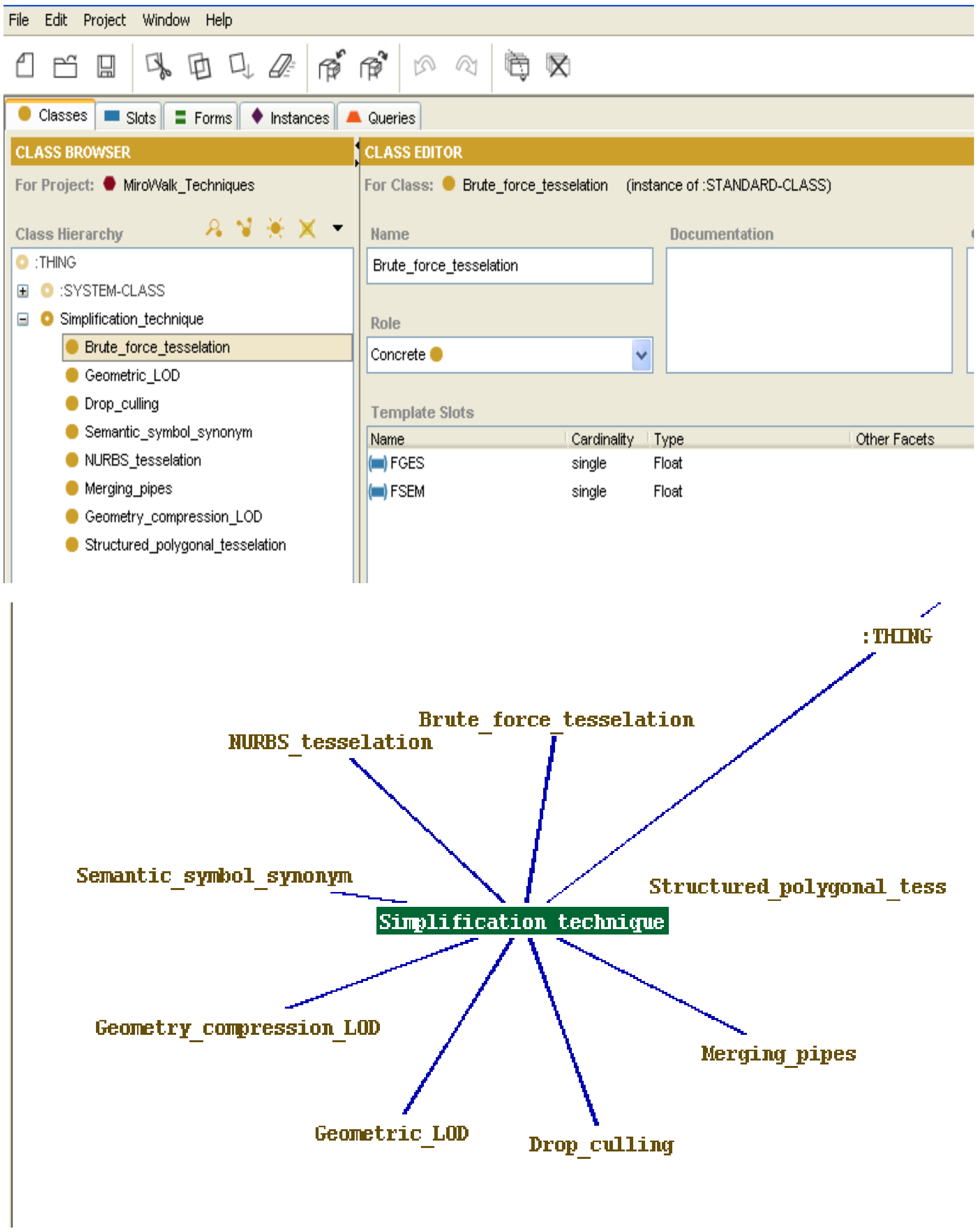


Figure 47. A screenshot with of some object based techniques modeled in the Mirowalk System

5.4 THE ADAPTIVE REPRESENTATION MODULE

I present in this section the *Adaptive Representation Module* of the system. This module receives the adapted model, as well as the parameters for graphical optimization of the final tessellated model displayed in the walkthrough viewer.

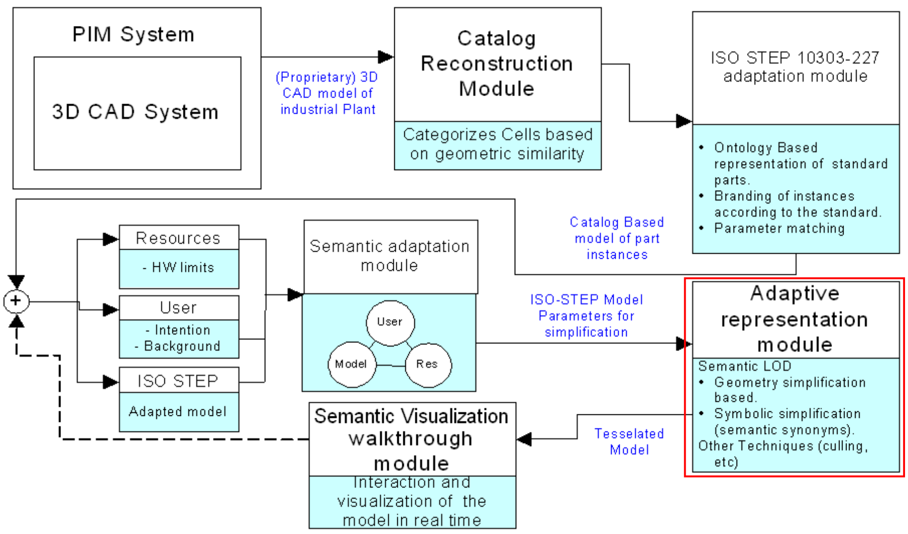


Figure 48. The Adaptive Representation Module – Fourth module in the generic architecture

I have implemented some representative techniques that are suitable for the generation of the final representation of the model for the Semantic Visualization walkthrough module. I will show several implemented techniques and will also discuss the advantages and disadvantages of using some of them in certain contexts.

I only chose to implement a limited set of techniques. Our focus of work was not to implement sophisticated techniques but to control optimization techniques using semantic criteria. Once implemented, the semantic decisions could, of course, also control more sophisticated techniques.

As it will be shown below, one of the important conclusions of this chapter is that the *semantic symbol LODs* is a special technique that produces good results balancing a moderate/low complexity in tessellation, with a medium/high semantic effect. The other techniques used are actually well known in the scientific community, but I have implemented them with special adaptations to be used in the context of our framework.

As I have explained before, I focus solely in *object-based* tessellation techniques, which complement other advanced rendering techniques (such as culling) which are not the focus of our work.

A clear advantage of our approach in this module is the ability to select optimization techniques on a per-part basis. Using the information of the reconstructed catalog the export system has control over the export process on a much finer granularity; instead of applying simplifications techniques globally it now can decide on a per-part basis which technique with which parameters should be applied. For example, instead of lowering the tessellation granularity for all NURBS in a model, the granularity can be selectively lowered for only a specific class of parts, similar to the approach of Brunetti, Stork, et al. in the development of the VDDP (Virtual Design Data Preparation) system for BMW [GBS02]

The decisions on a per-part basis are made considering information available through the semantic-triangle: information about the model, information about the user and its intention, and information about the resource. The logic for exploiting this decision is encoded in a set of semantic rules.

In the next subsections I explain the techniques used in our framework.

5.4.1 The Brute Force Tessellation Technique

This technique is basically a tessellation of a complex 3D CAD model into polygons for some 3D renderer, without any kind of additional information related to the CAD structure or even to the original geometric primitives used in the CAD system. Figure 49 shows schematically the principle of the Brute Force tessellation technique.

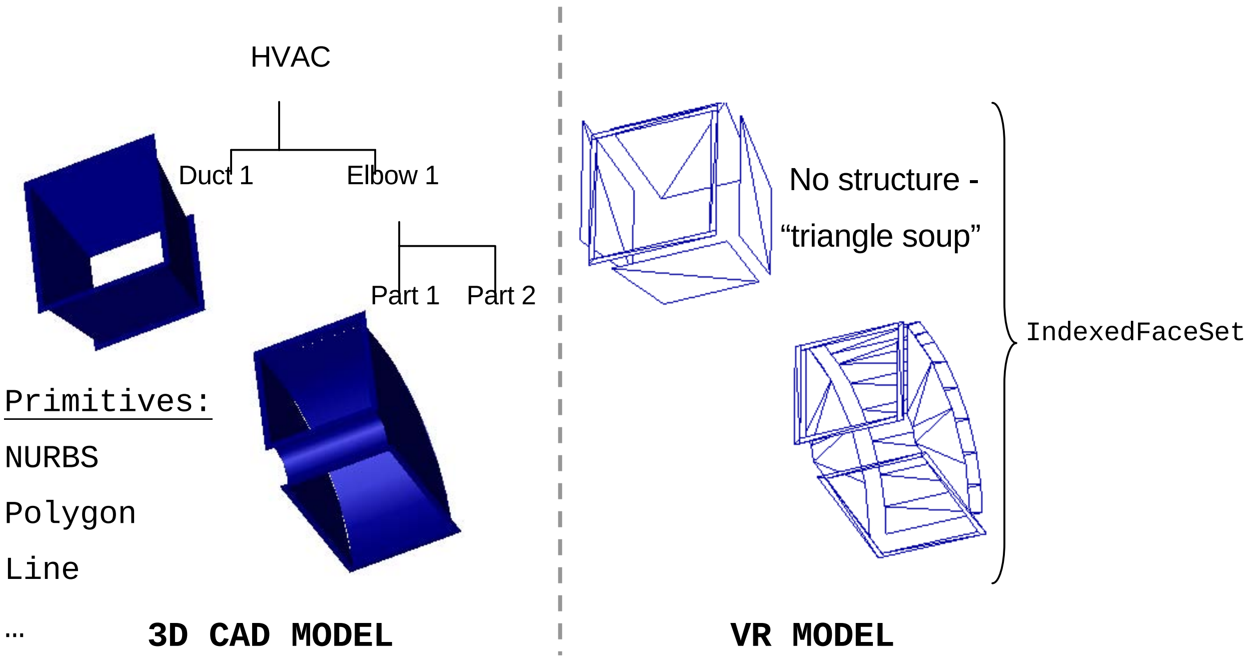


Figure 49. The Brute Force tessellation Technique – The naïve approach with unstructured triangle soup

Some of the characteristics of this technique are:

- The *visual quality* of the brute force tessellation is usually very good, but small objects tend to require an excessive number of triangles for rendering, and no simplification is applied.
- The main drawback from the performance perspective is the fact that the model is usually too complex and overloads the visualization system, demanding powerful resources and algorithms to visualize.
- The result is sometimes called *"triangle soup"* since the connectivity between the (arbitrary) grouping of triangles does not follow any pattern that can be used for semantic understanding, or the model beyond the mere graphical representation.
- The 3D CAD conversion to a VR model is blind, in the sense that no optimization is applied based on knowledge of the structure and nature of the model.
- Considerations about the potential user or the available resources are not considered at all in this technique.
- Basically, the geometric primitives are tessellated directly with some predefined algorithm which converts every primitive into a tessellated representations
- Sometimes the brute force tessellation technique can *improve* the navigation performance in frames per second of the visualization if compared to *structured polygonal tessellation,* since the overload for hierarchical structure in the rendering pipeline is reduced.
- Therefore, in some advanced systems for visualization of large models of Industrial Plant design focused only in visual inspection for Design Review, *structured polygonal tessellations* are considered as intermediate steps and converted into brute force tessellations.

Implementation comments:

I have implemented the brute force tessellation technique using internal API functions in the CAD system able to generate polygonal representation of most primitives. When this was not possible, I included our own algorithms to convert the primitives. I have ignored all structural or domain information in this technique.

After the polygonal representation was obtained, I have created a scene graph with the corresponding structures, such as `IndexedFaceSet` or similar.

5.4.2 The Structured Polygonal Tessellation Technique

This technique is basically the same than the *brute force tessellation*, but with the difference of considering also the grouping structures of primitives of the CAD system, and the relationships (mostly hierarchical relationships) between the parts of the models.

This is one of the most common techniques used by CAD systems, when they export the 3D CAD model to VRML or other similar formats.

Figure 50 shows an example of structured polygonal tessellation.

Thus, the main characteristics of this technique are:

- Basically the same visual quality than *brute force tessellation*
- Increased semantic content since :
  - o Grouping structures of the CAD system are preserved
  - o Naming of parts are preserved
- There is a high structural homology between the CAD model and the tessellated model. Thus, at least it is possible to know if a primitive is part of some grouping in a hierarchical structure, which may provide hints to the user about the functional role of that part.
- The performance of visualization is also low since the rendering pipeline requires an additional effort to traverse the scene graph, and the model is still converted with no consideration on user or resources. However, some algorithms (especially culling algorithms) may use advantageously the structuring of the model.

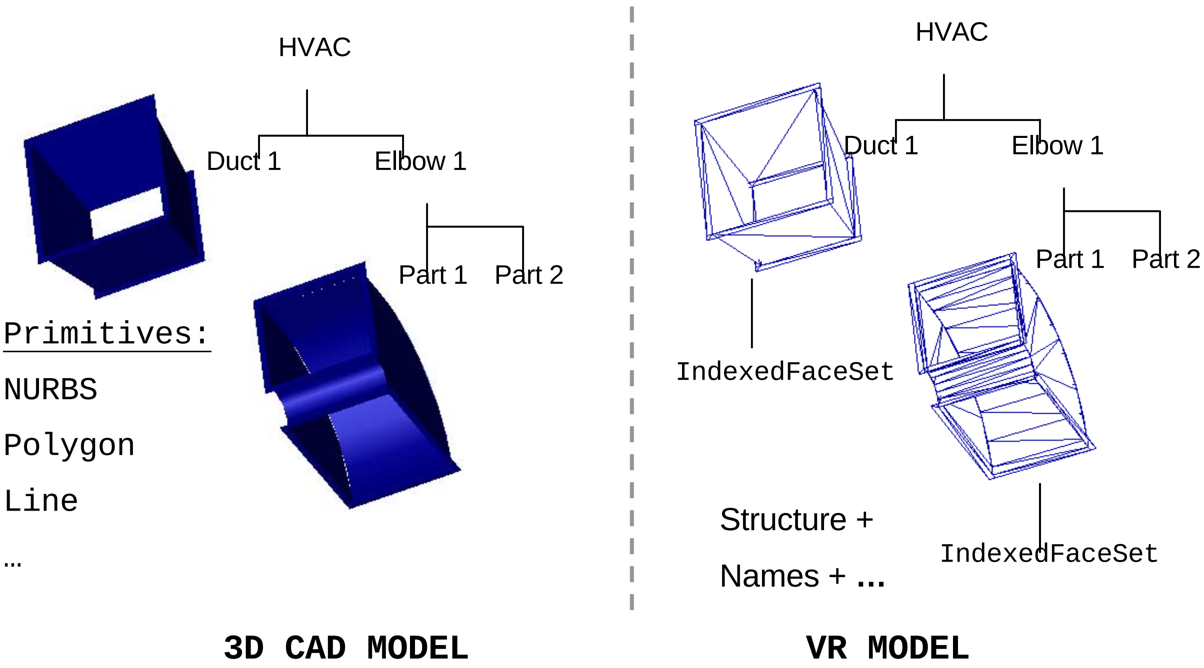


Figure 50. The Structured Polygonal tessellation Technique – an improvement since structure is kept.

Implementation comments:

The implementation of the structured polygonal tessellation technique is straightforward: with the API resources of the CAD modeller it is possible to query both the names and the hierarchical structure of the model. Thus, a simple replication of such structure in the scene graph can be done easily. However, complex relationships that can exist in the CAD model which are not *parent-child* may cause correspondence problems between both structures.

5.4.3 The NURBS tessellation technique

This is indeed an interesting tessellation technique to convert CAD models to VR environments, since by its own nature NURBS (*Non-Uniform Rational Bspline Surfaces*) are parametric mathematical surfaces. This allows on the one side a better control/steering of the visualization, and in the other side (although not straightforward as it seems) to preserve some of the parametric definitions of the 3D CAD primitives.

Some of the characteristics of this tessellation technique are:

- One of the most important restrictions of this technique is that **only few scene graph systems or specifications** for VR support NURBS as a basic type for rendering. For instance, VRML does not support NURBS in the standard (neither in version 1.0 nor in version 2.0). However, there are some powerful graphic APIs and scene graph systems supporting NURBS:

    - **Open Inventor** is one of the most suitable APIs for VR which includes NURBS support.
    - New APIs such as **Open SG** [REVB02], whose development is lead by Fraunhofer IGD, also has a module for the support of NURBS.

- The performance of visualization has the advantage that a single parameter (rendering complexity) can determine very fast the tessellation complexity of the mathematical surface, thus allowing dynamic adaptation in real-time of the surfaces described by NURBS in the SceneGraph system.

- If the CAD primitive is also a NURBS (as it is the frequent case in CATIA and Microstation, to quote two underlying CAD systems often used in Industrial Plant Design), the equivalence is straightforward. However, it may be the case that actually the CAD primitives are of other types, and during the conversion process they are transformed into NURBS. This happens for instance in Microstation with several primitives of SOLID and SURFACE types, which use internal calls to the geometric kernel (before ACIS, now Parasolid) to create a explicit representation of the object boundaries using NURBS.

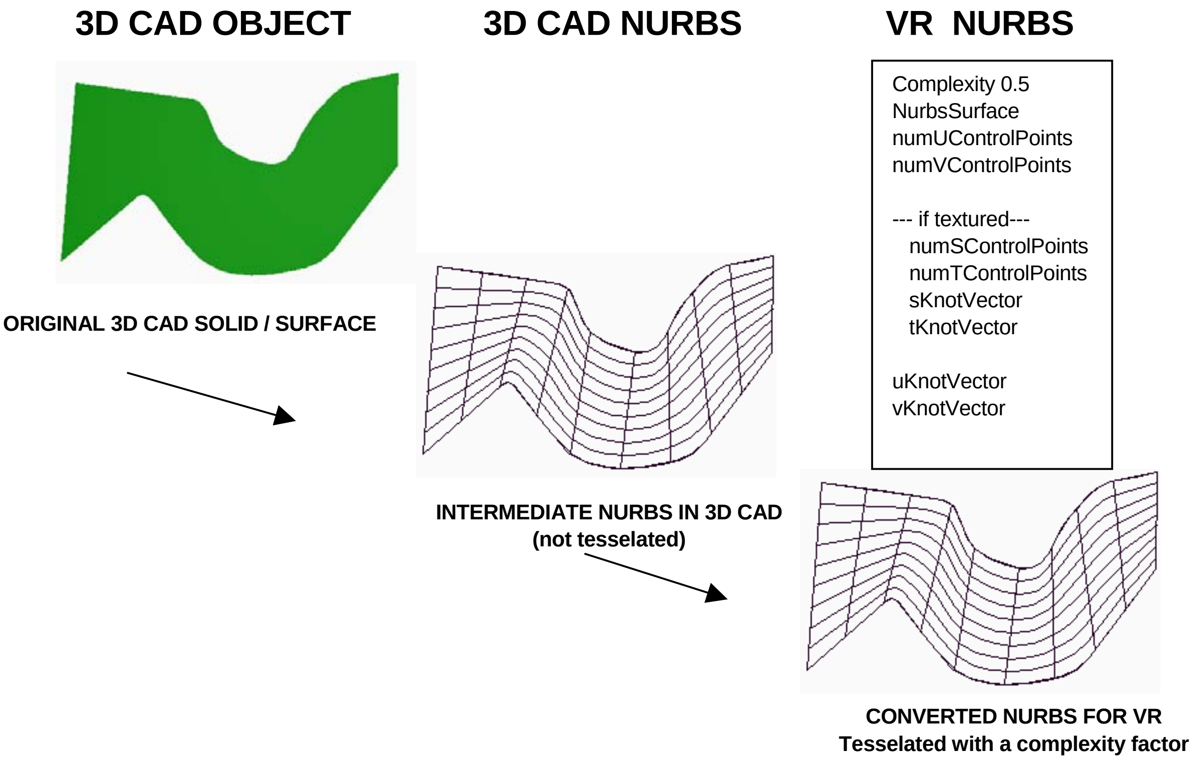


Figure 51. A NURBS surface tessellation in 2 steps : Solid to CAD NURBS, then to VR NURBS

- As a matter of fact, this is a technique that introduces a slight overhead in the tessellation, but the parametric control that introduces is very convenient to optimize walkthroughs.

- In general, an advantage of the NURBS representation is the possibility to have holes in complex surfaces, since a *trim profile* can be introduced in the parametric space *uv* of the surface.

- However, there is an important exception: *planar surfaces with holes*. Our experience tells us that this is a surprisingly common case in Industrial Plant Design models. This case should be detected and treated separately; a NURBS tessellation in this case is clearly too expensive.

Implementation comments:

The implementation of NURBS tessellation technique involves 2 steps. First, in case the object is not already a NURBS, a previous conversion to this mathematical representation should be obtained, typically using internal calls to the geometric kernel (ACIS provides this functionality) of the underlying CAD system. Second, the parameters of the surface (*control points in* u *and* v*, weights, knot vector,* etc.) should be obtained and translated to the scene graph system, that must support NURBS as well.

5.4.4 The Geometric LOD tessellation technique

This is one of the most common simplification techniques used to allow the representation with interactive rates (10 or more frames per second) of large 3D models. Basically, the concept is very simple, but extensive research exist on aspects and variants of this technique: The central idea is that an object, especially a complex one, does not have only one very detailed 3D representation, but *several representations* - discrete or continue- which *switch* between them depending on some external criteria of relevance in the current view (distance to object, size in viewport, budget of triangles, etc.).

Levels-of-Detail (LOD) methods render parts of the model that currently have a low impact on the visual appearance of the scene in a lowered quality and giving the sense of speed to the model survey and inspection. This is done by using a representation with fewer triangles or reduced textures. Level-of-Detail methods proved to be quite effective, especially if used with sophisticated methods of simplification as showed in ([HOP96], [GAH97], [VAM02], [LURC02]).

As seen in [BSG02] the main acceleration techniques used are basically visibility culling, object simplification and image based representations. Geometric simplification techniques (e.g. LOD, HLOD) give good results in handling massive data sets; the integration of Levels of Detail and good occlusion culling techniques are usually the key factors to achieve interactive rates in walkthrough systems [ASN00].

Level of detail techniques are explained and discussed in a very wide range of articles, but I recommend the book by Luebke et al [LURC02] where the most comprehensive techniques are explained.

To quote some of the latest advances in the field, in a recent article by Guthe and Klein [GUK04] a combination of quasi view-dependent hierarchical level of detail (HLOD) rendering was presented with priority-based streaming that is capable of rendering highly complex models at real-time frame rates at high quality even with a low network bandwidth.

Figure 52 shows an example of the basic concept of the Level of Detail (LOD) technique.

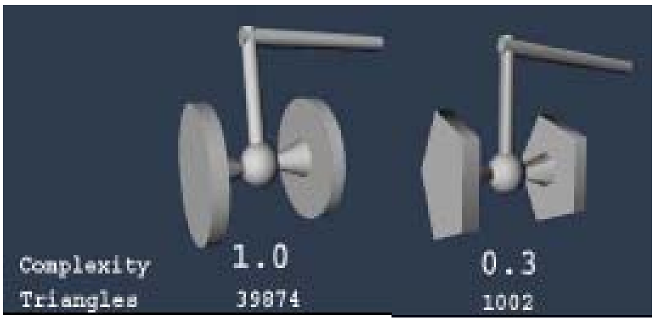


Figure 52. An example of Geometric Level of Detail (LOD) of an object – Complexity value effect.

The following are some special characteristics of this tessellation technique:

- Together with advanced *culling techniques*, LOD are one of the key techniques allowing the interactive visualization of 3D Industrial Plant CAD models.

- It provides an additional control of the tessellation cost since usually the LOD instances are static and their cost in number of triangles is fixed.

- The *static* LODs have the problem of important overhead costs in the rendering pipeline just for evaluation of the switching criterion, especially in the case of large models.

- Static LODs are mostly modelled by designers who take the original object as reference, and this manual operation evidently impairs the complete automation of the visualization experience (unless a library of representations is built incrementally).

- There are automatic ways of generating an LOD representation of a complex object (as for instance *geometry simplification* techniques, which removes vertices and edges), but the visual quality of the final result is not always guaranteed. These techniques are also costly in execution time, making conversion of large models of industrial plant slow. For instance, the worldwide reference project in the Large Model Visualization area of Plant Design (the *Walkthru Project* of D. Manocha, from UNC), takes a **whole day** calculating the LODs selected for representation.

- There exist also *dynamic LOD* techniques, which can be considered as an extension of geometry simplification techniques with a progressive approach. Thus, vertices and edges are added gradually to the object as more detail is required from the walkthrough. Again, the added cost makes these techniques suitable only if a short conversion time is not a constraint. The evaluation of thousands of parts for their instantaneous level of detail is also an impairment of performance during real time interactive walkthroughs.

- Visual discontinuity artifacts can appear while switching between different representations while the viewer is moving due to the massive characteristics of the data represented.

Implementation comments:

To speed up the rendering, LOD levels can be defined for certain highly distributed or some costly-to-render elements. For parts which are of high importance to the user or for parts that only produce a small number of triangles no LOD levels are needed.

The implementation of LOD in our framework had different forms:

- Bounding Box LOD: Simple and fast LOD generation based on bounding boxes of **small** objects (whose diagonal is less than a certain threshold). Elements below a certain size and distance threshold were rendered as bounding boxes. The representation was switched dynamically between the normal appearance and the bounding box, depending on the viewer's current position. The size and distance parameters could only be set globally for the whole model.

- Other criterion used was *distance camera object* (as suggested in LOD from Open Inventor): depending on the distance parameter, discrete LOD could be called accordingly. These LODs however required previous modeling or geometry simplification, whereas the *bounding box* LOD didn't.

- Finally, the relative size in the viewport (as a percentage of the area of the viewport) can also be used as switching criteria in our framework for purely geometric oriented LOD

5.4.5 Drop Culling LOD (Hiding parts)

Although most *culling techniques* are actually spatial-oriented techniques, there is a special case: the *drop culling* technique, which is object-oriented.

In this technique, the approach to speed up the rendering is to completely hide selected objects that are of very low importance to the user. Again the *rendering context* is the key; only semantic information about the user, purpose, model, resources allows the system to decide if an element of a specific class is of importance. In a sense, the *drop culling* technique is an extreme case of LOD with no graphical representation for an object.

Some of the main characteristics of this technique are:

- This technique has proved to be very useful in our tested large models of industrial plant. There are for example very small structures (such as clamps, bolts, etc.) whose tessellated representation consumes many triangles, and which in some adapted representations can be dropped, of course, only in case the semantic / geometric factors allow it for that specific case.

- There is an interesting variant of this technique (the *dynamic drop culling*), in which the objects are dropped only during movement, but once the user stops the objects are rendered.

- Actually, the only allowable situation for the use of this technique is that the $fsem$ and $fges$ factors have a minimum allowed value of 0.0 (see example in chapter 4).

Implementation comments

To mention a relevant example, a significant part of the triangles in a typical industrial plant model are produced by numerous little *clamps* that attach the *pipes* to a supporting metal frame. These clamps are relatively complex to render, but have a comparably small influence on the overall appearance of the model. Thus, for some users (most of them) the small clamps are of little interest when viewing the model. Therefore, I implemented a *semantic rule* to hide all clamps for specific users (Figure 53).

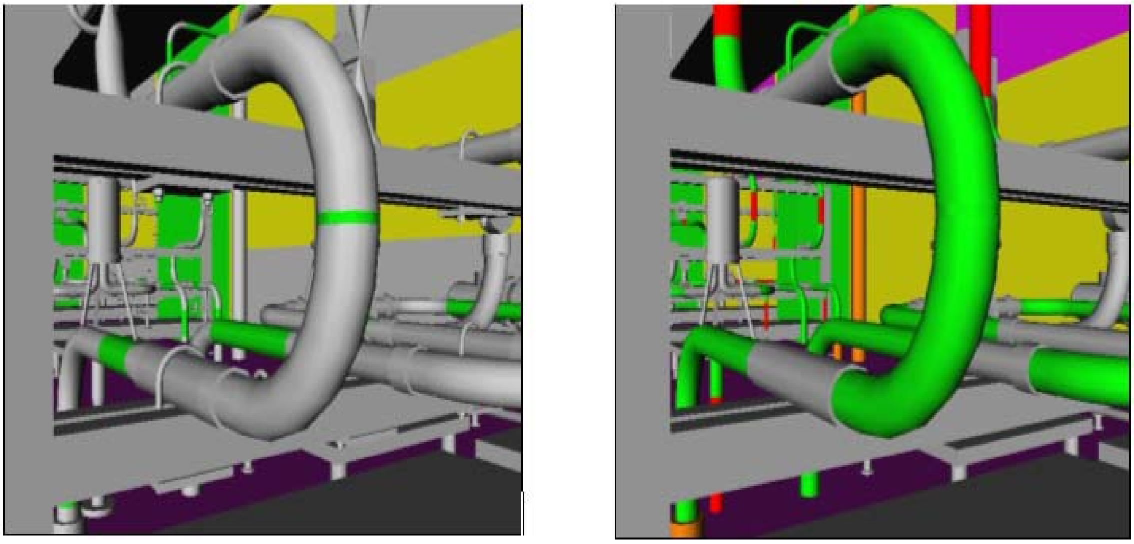


Figure 53. Semantic Rule: Render with drop culling technique. Left: With Clamps. Right: without clamps for specific user/purposes.

Hiding parts may not only make sense for speeding up the rendering, but also for enhancing the image quality or focusing the viewer's attention on certain sections of the model. Examples for this are hiding whole conceptual sections, hiding all doors and windows, or hiding the complete roof to allow a top view.

Dynamic drop culling:

This is a variation of the static drop culling technique. The main strategy is *to hide details and textures while the user navigates through the model,* and render the complete version once the viewer stops its movement. This approach produces discontinuity artifacts of disappearing elements, since a lot of geometry is hidden in order to maintain the frame rates. Commercial software such as NavisWorks or Mantra include this functionality.

5.4.6 Piping & HVAC Merging technique

This technique optimizes the way in which straight sections of HVAC & Piping structures are tessellated.

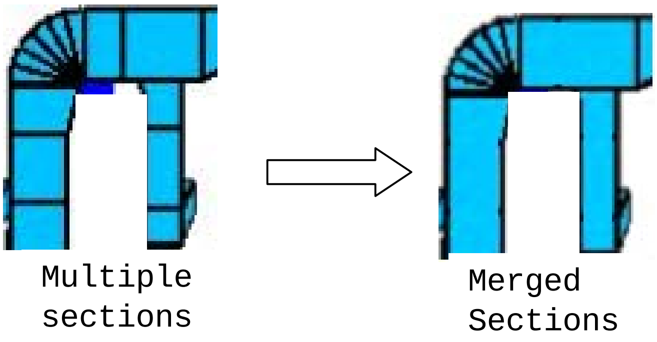


Figure 54. The Piping & HVAC Merging technique – joining of adjacent portions of piping structure

Basically, this technique merges consecutive sections that share a common top or bottom face into one longer straight section. This technique is in particular effective in model regions where long pipe sections are represented as several connected cylinders (Figure 55). If ***n*** pipe sections are merged to one cylinder the number of produced triangles is also reduced by the factor ***n***. As in most display systems the render performance is related only to the number of triangles, and not to the size of triangles, the render performance of this particular section will increase theoretically also around the factor ***n***.

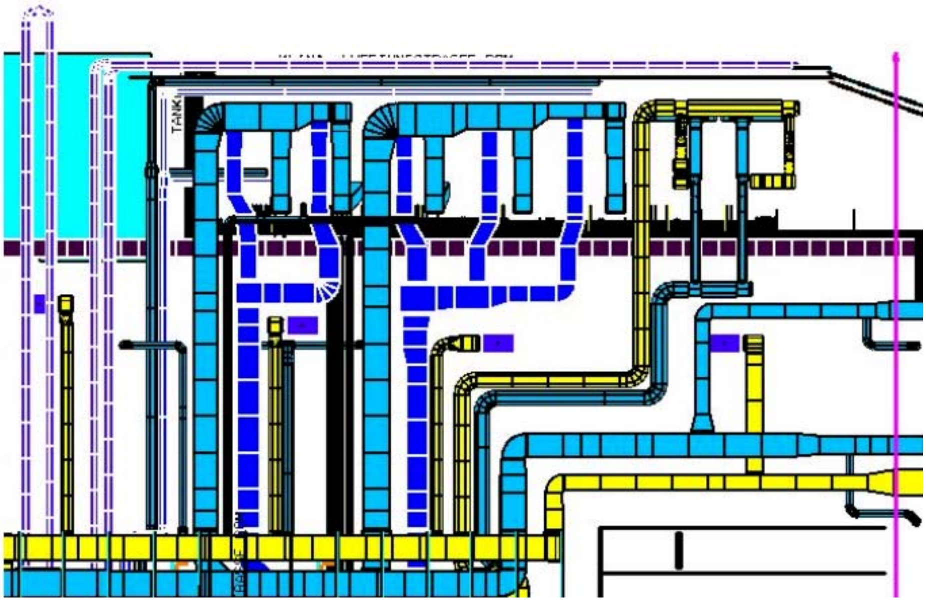


Figure 55. Part of a real CAD Plant model showing consecutive HVAC & Piping sections

Some characteristics of this technique are:

- This technique must be used *only* if the individual sections are not semantically relevant for the involved *user* and *purpose.* This is reflected in the calculated *fges* and *fsem* factors. Specialized HVAC engineers may not accept at all this technique, whereas a manager doing a client presentation may use it without problems.

- The visual impression of the exterior parts of the HVAC & piping section is exactly the same.

- The current implementation might be optimized for better performance in the calculation, although it works reasonably fast in current evaluated models.

Implementation comments

A pseudo-code example is shown in Figure 56, where I handle HVAC box sections (parallelepipeds). In an analogue way I also simplify other sections (e.g. cylinders):

```
while ( (j<6) && (howManyPlanesUnmatched <= 1))  /*Section Box*/
{
  k=0;
  j=0
  matchingFound=FALSE;

  /* Comparison of Section with current (planes)*/
  while ( (k<6) && (matchingFound == FALSE))
  {
    if (planeMatching[k] == FALSE) /* If TRUE, then matched before*/
    {
         matchingFound = AreCoplanar (FacePlanes_Section[j], FacePlanes_Current[k]);
             if (matchingFound == TRUE)
             {
                  planeMatching[k] = TRUE;
             }
         k++;
     }

     if (matchingFound == FALSE)
     {
          lastFaceUnmatched = j ;
          howManyPlanesUnmatched++;
     }

     j++;
   }

/* Then the boxes can be grouped, because exactly one plane of a face of
cornersSection doesn't have a corresponding plane in a face of cornersCurrent*/

   if (howManyPlanesUnmatched == 1)
   {
       blockFormed = TRUE;
       for (i = 0; (i<6) && (planeMatching[i] == TRUE); i++)
       {
        /* to get the face in Current not matched in 'i'.
           Then the final box is between the unmatched faces*/
       }

       // Assigns to cornersSection the enlarged box
       MS_GiveNewCorners(cornersSection, lastFaceUnmatched, cornersCurrent, i);
    }
```

Figure 56. Pseudo algorithm for Piping & HVAC Merging – joining adjacent piping sections

5.4.7 Semantic Synonym Symbol LOD

In this chapter I focus in a special use of the LOD technique that has reported substantial improvement in the walkthrough performance.

By means of the *Catalog Reconstruction* and the *Semantic Adaptation Module* I have recovered important semantic information about the parts of the model. Said otherwise, I have made implicit information available in an explicit form. Using this information I am able to replace complex parts with conceptual symbols that are much faster to render and nevertheless hold the semantic information associated by the user. The conceptual symbols are, so to speak, **semantic synonyms** for parts.

Figure 57 shows a part of the class valve that is instantiated in the model with a high distribution. The grey objects are valves rendered in their original form at different complexity levels. The red object is the symbol I used to replace the original valve. At a tessellation complexity of 0.3 this symbol can be rendered with 100 triangles instead of 1000 triangles that were needed for the original representation.

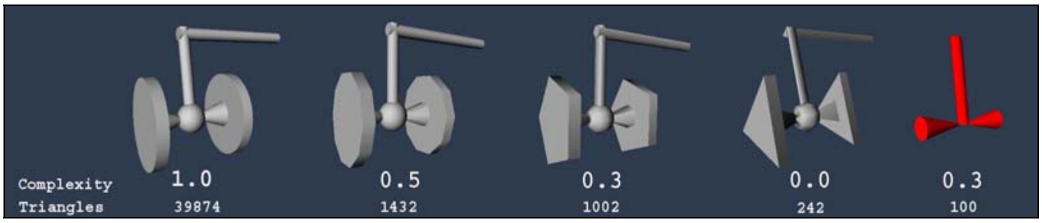


Figure 57. Valves at different complexities and a Valve -Symbol – the improvement is very high.

Replacing one valve in the model with a 3D symbol obviously only leads to a saving of a few hundred triangles, but if a lot of instances of this valve are present in the model the effect is multiplied. For instance, in one representative example I have tested, I got a triangle saving of almost **5%**. And since the valves are only one group of elements that can be replaced through symbols higher savings are possible. Figure 58 shows an example view of the chemical plant where a lot of valves are replaced with the valve symbol.

For a better visibility the valves are marked red, in a real application the valves would, of course, have their original color.

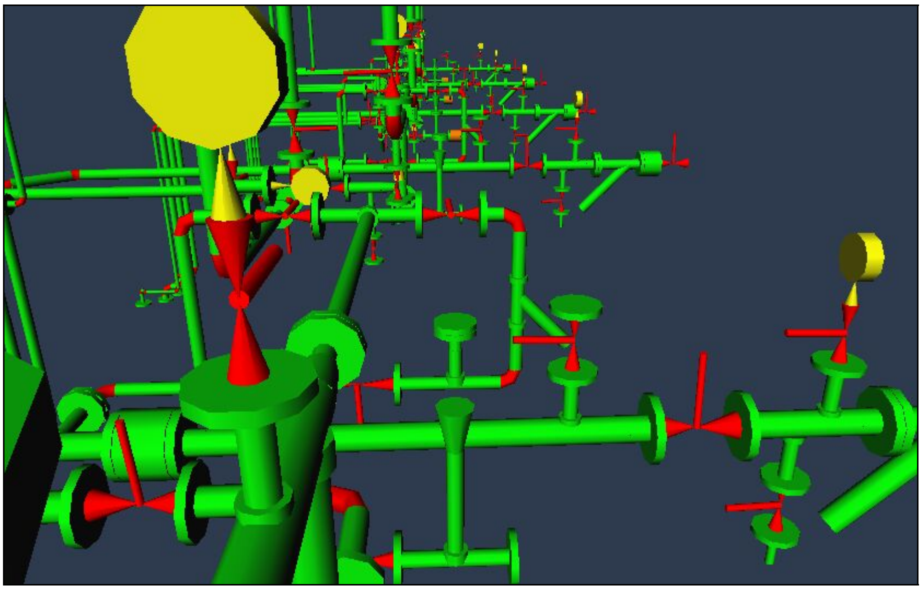


Figure 58. VR-View with a lot of Valve Symbols marked in red – Valves are easily understood

Another interesting alternative is to replace the valve with an object that has a complete different meaning. This is possible if the loss of information in this case does not have consequence – for example, if the user is not interested in the valves or does not even know what a valve is. Figure 59 shows the same view where the export system decided that valves are not essential and replaced them with simple pipe sections. The new pipe sections are marked in red. Again, in a real application the red sections would have the original color.

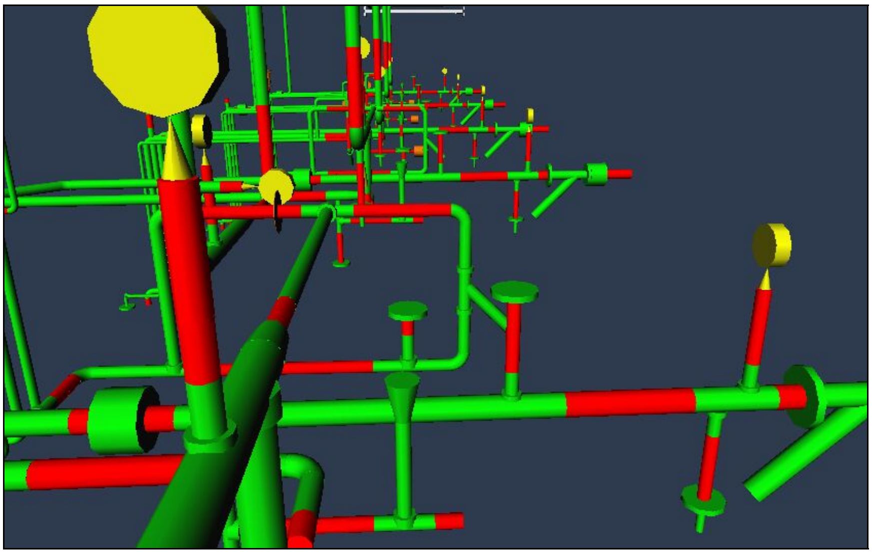


Figure 59. VR View with Valves and Flanges removed – Possible optimization for non-technical users

LOD techniques are based on a varying accuracy in the representation of a 3D object. Usually LODs are either automatically generated from the geometric definition of the object or they are modeled ad-hoc.

In both cases the geometric similarity between the LOD and the object is preserved as much as possible. On the other hand, the use of 2D symbols is a widespread engineering practice that is slowly moving also to the 3D representation [CAD05]**.**

Once the ISO-STEP adapted model is available, I generate alternative representations according to the parameters given by the previous module:

(i) I use parametric *geometric LOD* for those components of the model that have the largest influence in the number of triangles generated. These geometric LOD are based on the standard parametric parts of the ISO-STEP 10303-AP227 standard (instead of basing the LODs on the original 3D objects in the CAD model).

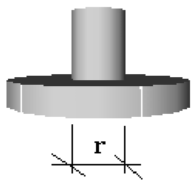
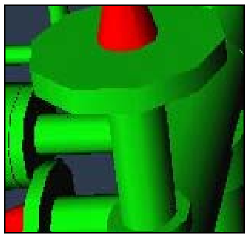
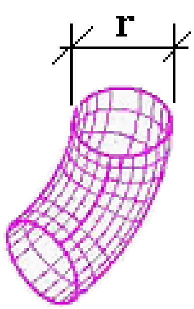
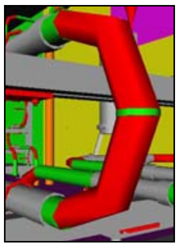
(ii) On the other hand, I generate in parallel **alternative 3D semantic symbols** for all components (e.g. 3D symbol for valve in Table 7, or just a straight line for a pipe section, etc.), which gives a much higher semantic compression ratio (better compression) without semantic loss for special user profiles and purposes. These semantic synonyms are

> *A special kind of symbol which graphically conveys the functionality and meaning of the represented object without exact adjustment to the physical dimensions.*

This of course depends on specific configuration of users/purposes, models and resources. Table 8 shows an example of the advantage of semantic symbols instead of pure geometric LODs. The Grey objects are geometric LODs generated automatically, whereas the red object is the symbol I used to replace the original elements. At a tessellation complexity of 0.3 this symbol can be rendered with 100 triangles instead of 1000 triangles that were needed for the original representation (see Table 7 for a relation of component vs. number of triangles for the geometric LOD – Semantic Symbol representation).

In Table 7 some ISO-STEP elements are selected to show the adapted representation and the elements to be matched (branding and matching as explained in Chapter 3).

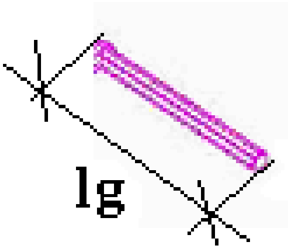
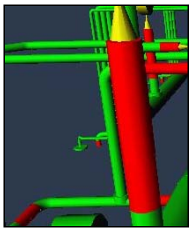
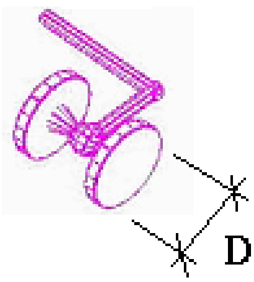
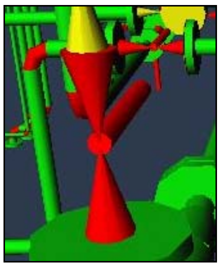
Table 7. Adapted representation of some components: geometric LODs and semantic symbols

3D CAD **(Geometric LOD)**	**Semantic Synonym representation (parametric)**	**ISO-STEP Matched parameters**
ISO-STEP 10303-AP227 FLANGE (COD. 4.2.84)		
	 **r** = radius **s** = side **XYZ** = Coord. System **P** = position (px,py,pz)	**STEP 4.2.84.3** Hub through length = s **STEP 4.2.84.4** hub weld point diameter = 2*r **STEP piping** connectors : give XYZ, P.
ISO-STEP 10303-AP227 ELBOW (COD. 4.2.66)		
	 **r** = radius **n_div** = # of divisions **XYZ** = Coord. System **P** = position (px,py,pz) **alpha**= angle	**STEP 4.2.66.3** centreline radius = r **STEP 4.2.66.6** Sweep angle = alpha **STEP piping** connectors : give XYZ, P.

As it is shown in the Results section (Chapter 6) and in the Mathematical Model chapter (Chapter 4) the semantic symbols reduce dramatically the amount of triangles required for the tessellation of the object. For instance, to quote only one example, an ISO-STEP 10303 valve is tessellated with the following values:

- Brute force tessellation : **48710** triangles
- Pure Geometric LOD : **1302** triangles (maximum compression)
- Semantic Synonym : **100** **(Notice the radical improvement)**
- Ratio Semantic / Geometric LOD **7,68%**

Table 8. Adapted representation of some components: geometric LODs and semantic symbols (continuation)

ISO-STEP 10303-AP227 STRAIGHT_PIPE (COD. 4.2.232)		
	 **c** = complexity **r** = radius of joint **XYZ** = Coord. System **P** = position (px,py,pz) **lg** = length	**STEP4.2.52.3** end to end length = lg **STEP piping** connectors : give r, XYZ, P.
ISO-STEP 10303-AP227 VALVE (COD. 4.2.264)		
	 **c** = complexity **r** = radius of joint **XYZ** = Coord. System **P** = position (px,py,pz)	**Special case**: No geometric parameters defined in STEP 10303-AP227. (However semantic synonym is parametric)

5.4.8 Other techniques implemented

Here I mention some other techniques I have implemented, and that can be used in our framework as well.

5.4.9 Custom Complexity for Surfaces

In a similar way to hiding specific parts I also set a custom tessellation complexity to specific parts. Again the decision is based on the importance of the element for a specific user. The importance is derived from the user's profile and his intention.

The best way to explain this technique is with an example: An engineer who is reviewing the piping system of the process plant model is not dependent on "*nice looking"* pipe elbows. The only information he is interested in is whether the model contains all needed elbows and whether the elbows are in the right position and orientation. A coarse representation of the elbow using just a few triangles is therefore sufficient, even though it might look edgy (Figure 60 and Figure 61). On the other hand, the polished appearance that is desired if the model is presented to a customer might be disturbed by the edgy elbows. Once again a simple semantic rule will formalize this matter.

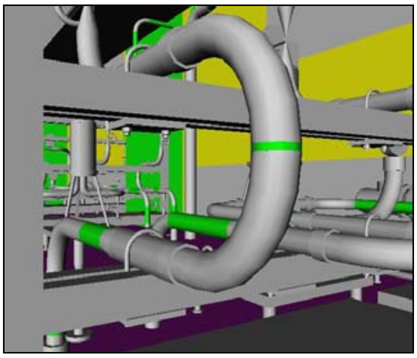


Figure 60. A Smooth Pipe Elbow

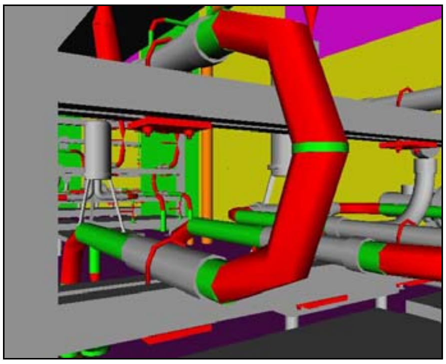


Figure 61. A coarse Pipe Elbow

5.4.10 Model Compression using Repeated Elements

A neat side effect of having information about the repeated instances is an easy- to-implement compression method for the VR files. Instead of exporting each instance of an element class separately, the element is only exported once and later referenced using a transformation to move the element into the right position and orientation. The size of our example models were reduced by around 30% to 50% using this simple technique.

Unfortunately, this compression method has no effect on the memory footprint while viewing the model. This is because the compressed way of storage is inflated again when the model is loaded into the main memory by the viewer; the Open Inventor scene-graph contains a copy of each instance instead of referencing a shared template. However, this is specific to the viewer I used; a viewer that takes advantage of the compressed representation could be implemented.

5.5 SEMANTIC VISUALIZATION WALKTHROUGH MODULE

In this section I present the *Semantic Visualization Walkthrough Module*, which is the module where the visualization of the final tessellated model (coming from the *Adaptive Representation Module*) takes place. Once the different semantic additions are incorporated into the model, it is ready for visualization in a walkthrough system.

The main visualization experience occurs in this module, and it is here where the ***user*** can actually use the VR visualization of the ***model*** in order to fulfil her/his ***purpose***. The model representation is exactly adapted to fit the needs of the user.

In the Design Review Walkthrough module (Figure 62). I implemented the techniques described in the previous section plus other standard techniques (including some *culling* implementations) already provided by the Scene Graph API selected, TGS Open Inventor 5.0. In the software application I have developed (*MiroWalk*), this module is called "*MiroWalk viewer*". The *MiroWalk viewer* application is actually tightly linked with other modules of the framework, and I will present the *Mirowalk* system shortly in this chapter for convenience, explaining the viewer functionality as well.

This visualization tool is a stand-alone application and includes tools for pan, zoom, and navigation in real time. The collection of cells in a tree hierarchically structured appears at the left side of the scene, allowing the selection of a given cell or group. Other possibilities present in the viewer are the per-part identification; the seek function and the possibility to manipulate the parts (move spatial position, scale, etc).

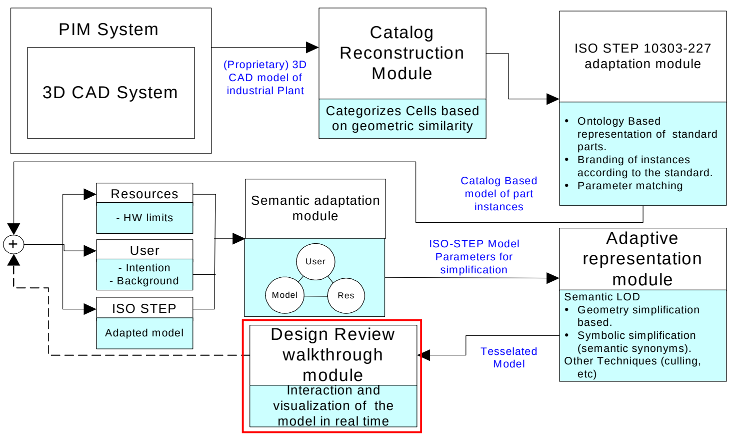


Figure 62. The Semantic Visualization Walkthrough Module – Fifth module in the architecture

5.5.1 Some Implementation Details of the MiroWalk Software System

The software system (in the form of advanced prototype) that integrates all modules of the architecture is called ***MiroWalk***. This system has been successfully used to perform Design Review purposes of complex models of Plant Design in several research projects of Fraunhofer Institute for Computer Graphics and other institutions of the INI-

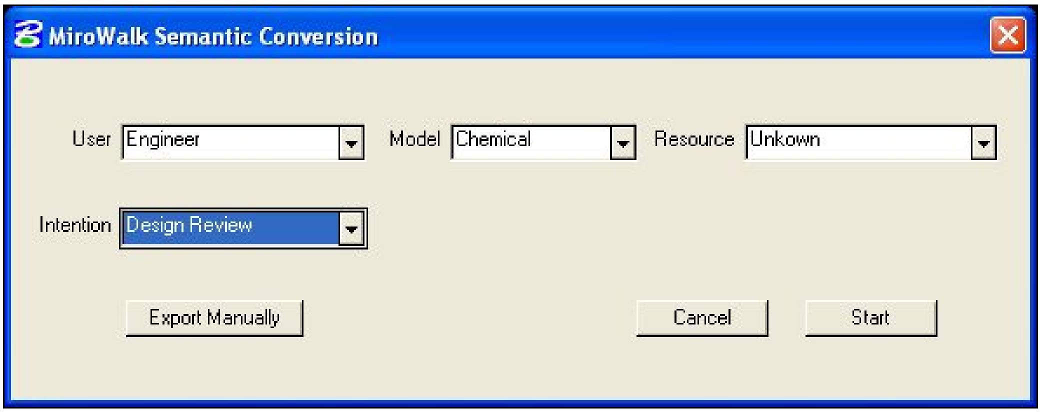
GraphicsNet. To recall shortly the concrete implementation APIs used, I present a summary of features.

Table 9. Some features of the Mirowalk Software system

Feature of the system	**Details**	**Comment**
3D CAD system used	MicroStation V8 AutoCAD R14	The **.dgn** format is used by all Bentley and Intergraph products for Plant Design. As Microstation provides an advanced API to develop applications and operate on .dgn models, I have chosen this CAD software as the main underlying 3D CAD system. Also, all the 3D plant models (more than 10) that I have studied were specified in this format, although coming from different systems. Support for AutoCAD R14 is provided (using the *ARX* API), although with less functionality.
API for geometric querying and processing	MicroStation Development Language **(MDL)**	This API gives advanced CAD functionality, especially access to the geometric kernel (ACIS / Parasolid) of the MicroStation system. The CAD geometry is accessed through the MicroStation MDL API that provides an interface for scanning and reading cells and element The 3D CAD model is analysed and transformed according to the module architectures using this API for geometric functionality (especially in the conversion process).
Programming Language for geometric functionality	C C++	MDL has versions in Java and C/C++. I have mainly used the C interface for performance reasons.
Ontology tools and languages	Protégé 2000 OWL Plug-in	I give the details in the specialised chapters of this work. Protégé is mainly used to edit the ontologies, and OWL to process them
Scene Graph API Selection	TGS Open Inventor 5.0 Open SG	This API provides advanced SceneGraph functionality and the most advanced prototypes for the visualization tools are implemented in this API. The support of NURBS and the compatibility with several visualization tools were important when selecting Open Inventor as the Scene Graph tool to use. Concretely, the *MiroWalk Viewer* presented in this chapter is implemented in this API. I have started as well to test some prototypes in Open SG.

To give an overview of the system complexity, the geometry conversion classes and routines an the tessellation techniques implementation have approximately 13.000 lines of code; whereas the catalog reconstruction and ISO-STEP/Semantic adaptation tools have about 6.000 lines of code, and the Visualization Walkthrough module about 16.000 lines of code.

Figure 63 shows a screenshot of the semantic conversion tool, implemented in MDL (for the catalog reconstruction and adaptation to the standard)



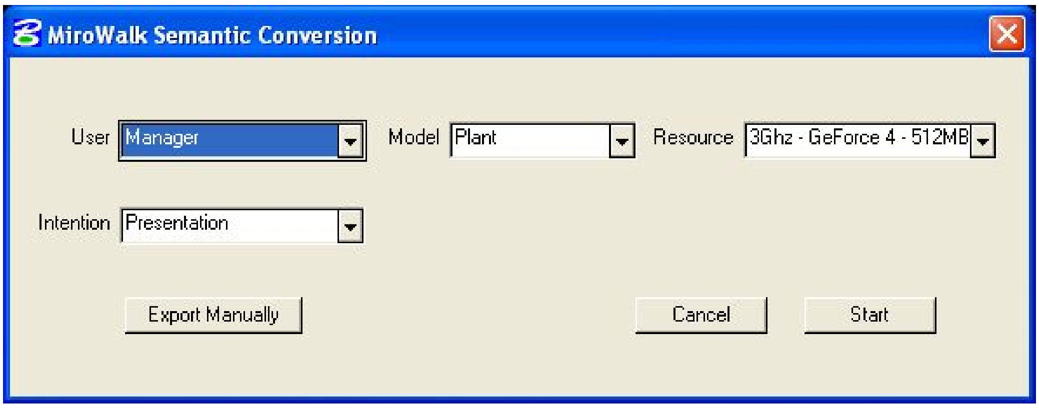


Figure 63. Screenshot of the initial dialog of Mirowalk system with definition of *user, purposes, model* and *profile* – these simple input parameters help to define the conversion strategy

To give a simplified example of how the conversion works, a simple sequence diagram for exporting a *cell* is shown in Figure 64 I omit several details (including ISO-STEP standard adaptation) to give an idea of how the classes interact. Initially the Conversion Tool has to initialize the ontology module to set the semantic context. Figure 63 shows the initial dialog that asks the user for the conversion context.

During the export process the CAD model's cells are read one-by-one from the model-file and are written to a new file as Open Inventor primitives. For each element the catalog module is called to determine the class of the cell. Subsequently the ontology module is called to get information on how to export this particular part and which techniques are to be applied. In this fashion the conversion tool ties together the ontology and the catalog module.

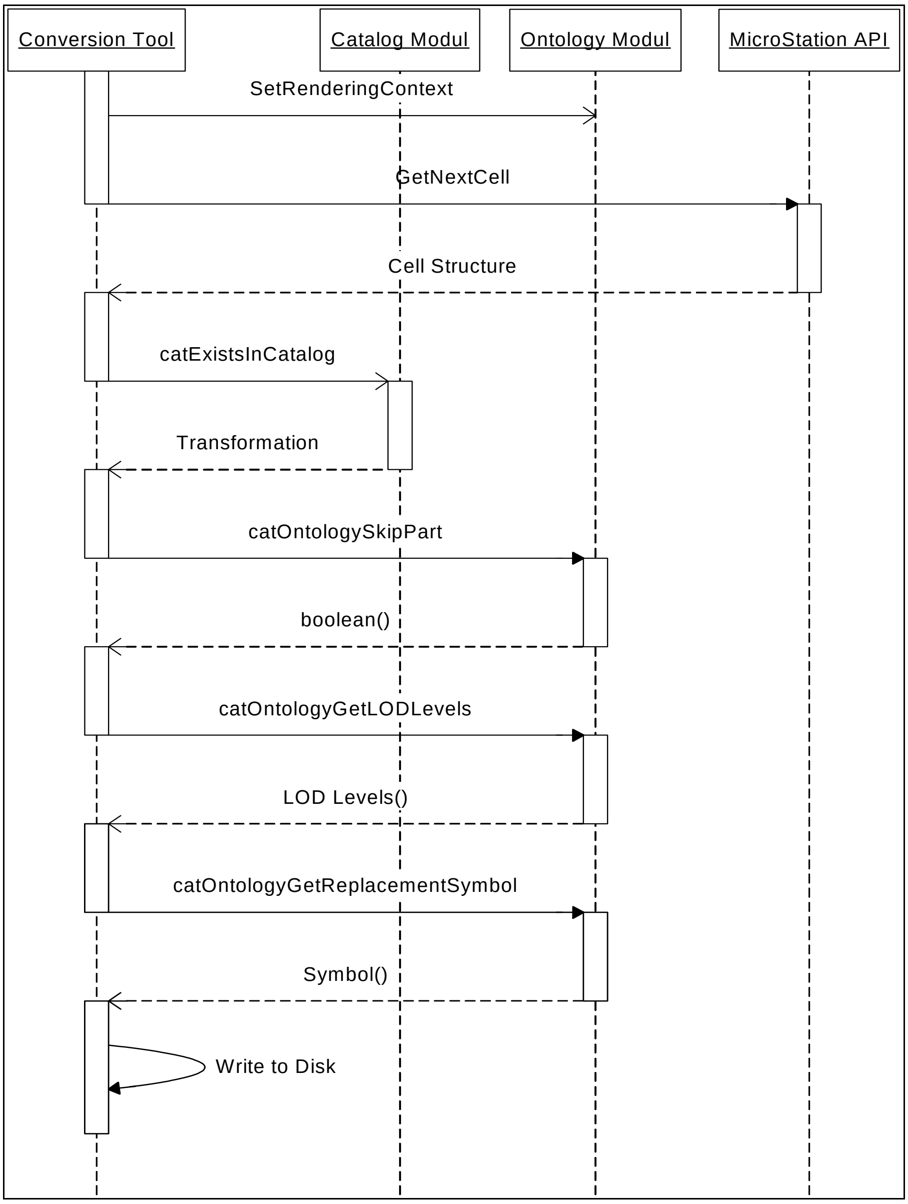


Figure 64. Simplified UML Sequence Diagram for Exporting a Cell – assuming only Drop culling, Geometric LOD and Semantic Synonym techniques

When the Conversion Tool is started, an initial dialog lets the user select a target file, and a subset of levels.

The user then has to set a list of parameters that specify how the model should be exported.

5.5.2 MiroWalk Viewer: An implementation of the Semantic Visualization Walkthrough Module

The MiroWalk Viewer is used to visualize and navigate the resulting file in a 3D virtual walkthrough environment. The viewer is a GUI application based on the *Microsoft Foundation Class* framework and uses the Open Inventor library from TGS for rendering.

The final adapted model which will be used by a specific *user*, who wants to do a special *purpose*, is displayed and navigated in this visualization module.

Rendering and navigating the scene is fully handled by the Open Inventor classes. The MiroWalk Viewer extends the Open Inventor classes with functionality needed for engineering visualization, like measuring of distances, hiding selected parts of the model etc.

With the optimisations of the global architecture, the model coming to the viewer can display interactively complex CAD models of Industrial Plants at interactive frame rates of 10 fps or more.

Some of the characteristics of this module are, to name a few:

- *Support for different HW set-up*: Depending on the available resources (workstation, PC, large screen, input devices, etc.) the viewer adapts the visualization to the existing resources.

- *Structural information*: The viewer supports the hierarchical tree metaphor to display the internal structure of the 3D CAD model.

- *Parts Catalog*: It shows the relationship between the geometric elements and the categories coming from the ISO-STEP standard.

- *Advanced Navigation Modes*: It supports the *walk* navigation model (always parallel to the ground), *fly* navigation model (free camera movement in 3D space), *examiner* (the camera rotates around the object), etc.

- *Selection and manipulation possibilities:* Each individual object can be selected, interrogated and manipulated.

- *Status bar*: To inform the user about relevant events and provide him with related data to his purposes.

Figure 65 shows a screenshot of the viewer as well as some available options.

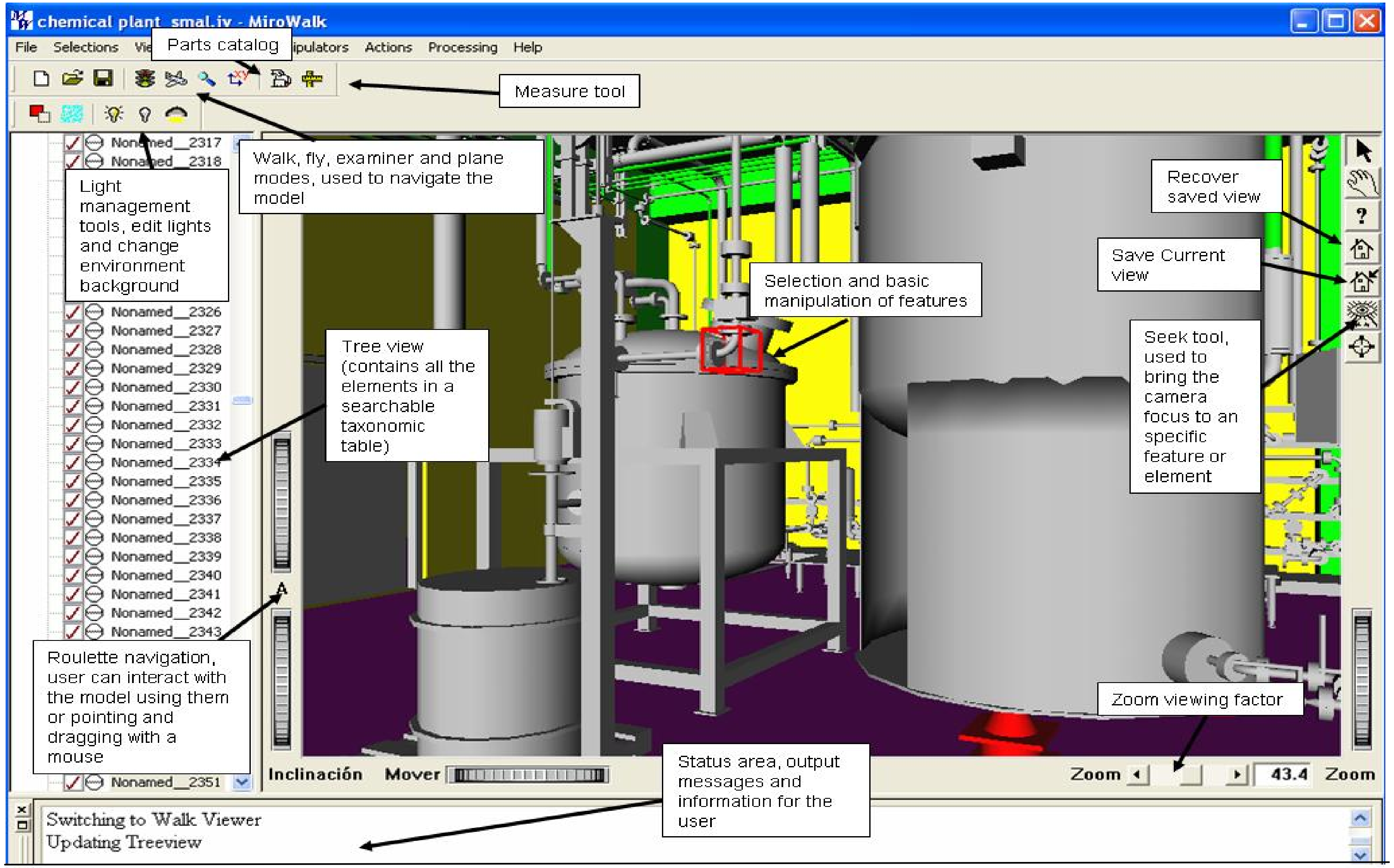


Figure 65. MiroWalk Visualization Module – Several options for interaction and manipulation are available. The user can make interactive walkthroughs on the adapted model