General AEC Reference Model (GARM)

An aid for the integration of application specific product definition models

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The General AEC Reference Model (GARM) is developed for AEC applications within the ISO/STEP standardisation effort. The goal of this standard is to facilitate data-exchange between computer-applications for design, production and maintenance of discrete products, including products for the Architecture, Engineering and Construction (AEC) Industry. The major difference between STEP and other data-exchange formats, such as IGES, DXF and SET, is that STEP-files or -databases will be directly interpretable by advanced computer-applications without human interaction. The other formats allow only the exchange of drawings or 3D geometric models which are intended for human interpretation. GARM will be the integration model for AEC applications in the STEP standard; its high level of abstraction makes it usable for a variety of applications and products, and eases the development or adaption of generic software products.

STEP and PDES

STEP, STandard for the Exchange of Product-model data, will be an advanced standard for the exchange of product definition data. It will support the development of an *open* integrated computer aided design and construction environment. STEP will also be the first *international* standard for data exchange; it is a logical successor of current (de facto) national standards such as the US IGES, the French SET, the German VDA-FS and VDA-IS, and system-dependent standards such as DXF and SIF.

Unlike IGES, STEP will not only support the exchange of data via (neutral) files. Although the first version of STEP, anticipated to be published in 1990, will be very much oriented towards such an exchange principle, it will also support the use of shared databases and knowledge-bases.

The major difference between STEP and IGES however, will be the fact that STEP deals with product-model data which are intended for direct use by advanced computer applications. IGES information was (and is) intended for human interpretation at the receiving site. This does not mean that STEP will not concern itself with the exchange of technical drawings. Although the core of the standard will be formed by a computer-interpretable product model, it will support also the exchange of (human oriented) product presentation data, including 2D drawings. These presentation data will be derived from the original product model.

The STEP activities started several years ago under Sub-committee 4 of ISO Technical Committee 184 (Industrial Automation Systems). This Technical Committee deals also with control languages for manufacturing, robots and NC-machines, and standards for the highest level of the OSI (= Open Systems Interconnection) reference standard.

A leading role in STEP is played by the US. The US equivalent of STEP will be called PDES (= Product Data Exchange Standard). The PDES organisation completed an initial study for the standard in 1986. This so-called PDES Initiation Effort sketched the outlines of the work to be done. Many concepts in STEP which are still in use, originated from this effort. The most important one is the three layer approach, which is very much based on the three-layer concept of the ANSI/SPARC reference model for data-base management systems. STEP has an:

- *Application layer*. This layer is intended for the definition of Application oriented reference models. The contents of the application layer are not part of the standard itself; it will be used to develop the standard and provides a "proof of concept" that data between applications can be exchanged by means of it. Entities which belong to the application layer are mappable on entities in the logical layer.
- *Logical layer*. This contains the logical definition of the standard. It is an integrated model, based on the models developed in the application layer.
- *Physical layer*. The Physical layer defines how information can be exchanged, using physical file formats or database formats. This layer will also be part of the actual standard, otherwise it would be impossible to exchange data physically.

STEP will concern itself with a variety of product-types. Three major classes of products are currently defined: Mechanical products, Electrical & Electronical products, and products of the AEC (= Architecture, Engineering & Construction) industries.

The actual work on the standard is not done by TC184/SC4 itself. The sub-committee has formed a working-group (WG1) which does the job. This working group has split itself again in various sub-groups, working on different parts of the standard. Models are made for the following topics:

- Geometry and Topology. This includes wireframes, surface models and solid models. Three classes of solid model representations will be supported by STEP: Exact Boundary representation, Facetted Boundary representation and CSG-representation.
- FEM (= Finite Element Model)
- Tolerances (Geometric Tolerances)
- Form Features

- Materials
- Product Structure Configuration Management
- Presentation
- Drafting

Apart from these, several models are made for specific application areas such Electrical & Electronical, and AEC.

AEC in STEP

Currently, six models are developed within the AEC committees of PDES and STEP. Let me give a brief overview of each of them first.

- *Building Systems Model.* This model [4] is developed by Prof. James Turner of the University of Michigan. It can be characterised as a model which shows the decomposition of building systems into sub-systems, the connectivity of these systems and sub-systems, and the (semantical) classification of building systems and components.
- *Ship Structures Model.* The Ship Structures model [6] is developed by a team operating within the NIDDESC project of the US-Navy. It contains a variety of constructs and principles for the modelling of ship structures, including specific topology and form features.
- *Ship Outfitting Model.* This model [7] is also developed within the NIDDESC project. Work has recently started, so that a characterisation cannot be given yet.
- *Plant Design Model* [5]. Developed by CADCOM in Norway. CADCOM is an organisation (and also a company) which supports the exchange of data between computer systems used for the design and manufacturing of oil rigs and plants in Norway.
- *Distribution Systems Model.* Developed by Pat Rourke of Newport News Shipbuilding in the US. This model is intended as a general model for distribution systems, including HVAC (= Heating, Ventilation and Air-conditioning), electrical distribution, water distribution, etc.
- *General AEC Reference Model.* This model [2] was originally proposed by the author as an aid to combine and relate the various specific models developed within AEC and elsewhere in the STEP/PDES development. It is now used as the "integrator" model within AEC.

Apart from these activities which have a strong liaison with the STEP/PDES development, there are several other national and international projects of importance. They do not contribute directly to the standard, but they make use of the concepts developed so far, and they may have some influence later on.

I would like to mention here the Finnish RATAS project aiming at data exchange and application of advanced information technology in the Finnish AEC industry, the Eureka EU130 project "CIM for Steel Structures" which bases its data-reference model on the

General AEC reference model of STEP, various projects in the Netherlands done by Rijkswaterstaat (a governmental body responsible for public works such as roads, canals, bridges, dikes, etc.), and the Dutch Programme for Innovative Research IOP, aimed at the development of an Information Infra-structure in the Dutch Building Industry. Some large research projects which are initiated for ESPRIT II in Europe, starting in 1989, will also contribute directly or indirectly to this development.

Integration and planning

It will be clear that the ambitious an huge effort undertaken by the PDES and STEP committees, with many parallel national and international activities having more or less the same goal, are difficult to co-ordinate and to direct towards one consistent result. Integration of the various models has been the major issue during the last year, and will continue to play an essential role in the next couple of years. Two major integration activities have been undertaken so far: one under the PDES flag as the PDES Integration committee, another under the STEP flag. Both activities did not lead to the level of integration required for a consistent, unambiguous international standard. The major problem in STEP and PDES is that experts started to make models for various topics or areas of interest, without a clear understanding of how all the pieces fit together. For this purpose, the need of a *STEP Planning model* was recognised. Several attempts did not lead to results. For some time, the General AEC Reference Model (GARM), mentioned before, was seen as a candidate planning model. GARM is however not global enough to serve this goal. Recently a new planning model for STEP was proposed [1] based on discussions in the STEP Planning committee and some fundamental modelling concepts borrowed from systems-theory. This planning model is based on three "modelling spaces" to represent or present product-information:

- Product Model Definition Space
- Product Model Representation space
- Product Model Presentation space

The Product Model Definition Space shows the interrelation between various abstractions in Product modelling theory. The Representation Space contains models which are oriented towards the modelling of Aspects of products. For example the analysis and/or simulation of the behaviour or derived characteristics of the product, such as strength, durability, costs, etc. They make use of various representations of the product. The third one, Product Model Presentation Space, contains presentations of the product information for human interpretation, such as 2D drawings, shaded images, texts, tables, etc.

The Product Model Definition Space recognises three fundamental abstraction methods:

- *Generalisation/Specialisation.* Entities can be very general or more specific for an application area. The specific entities can be defined as sub-types of the general entities, thus inheriting methods and rules from these entities. Relationships between entities showing the generalisation/specialisation concept are typically "is-a" relations.

- *Aggregation/Decomposition.* This abstraction is used to model the decomposition of complex products or systems into component or sub-systems. Relations between entities showing this concept are typically labeled as "is-part-of" or "contains".

- *Characterisation.* The characterisation abstraction is used to define characteristics or aspects. They are typically modelled as "is-aspect-of" or "is-characteristic-of" relations.

These three fundamental abstractions are extended by a fourth principle, showing the products *life-cycle.* As a result, we are now able to classify each model and each entity in their own modelling space.

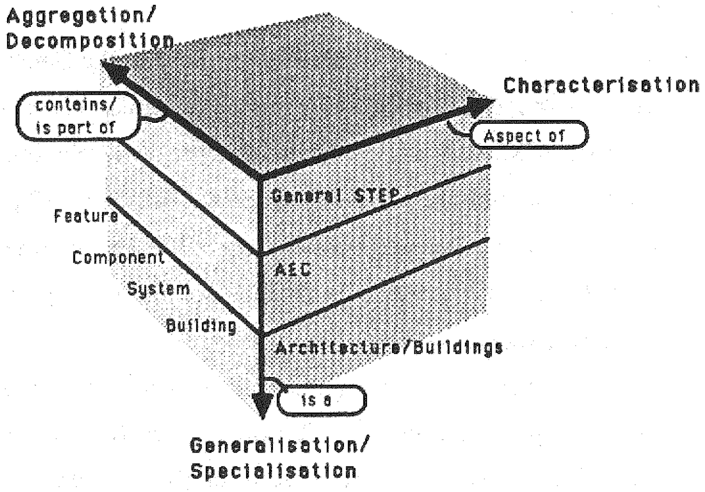
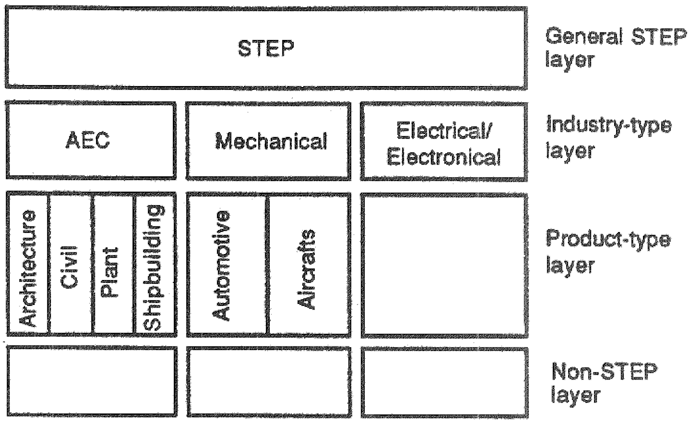


Fig.1 The three abstractions which define Product Model Definition Space. The life-cycle is not included in this picture.



Generalisation/Specification

Fig.2. STEP models can be classified as general, industry-specific, or product-specific. GARM is seen as a general model which serves the needs of the whole AEC industry. More specific models are made for Architecture, Plant Design and Ships. They define the specific needs for these products, but inherit the general properties etc. of the GARM.

GARM today

The concepts mentioned before can also be found in the General AEC reference model (GARM). GARM is in fact developed as a model that links the various modelling concepts within and outside AEC. It is a high level, abstract data reference model, sitting on the second level of the Generalisation/Specialisation axis of the STEP planning model. Product specific models which are developed by members of the AEC committees of PDES and STEP will make use of the generic concepts in GARM, but add specific data-structures and more meaningful entities to the model [3].

The model is based on one generic entity which represents a product or a decomposition of the product: the Product Definition Unit (PDU). A PDU has characteristics, which refer to certain aspects of the product. Examples of aspects are strength, costs, safety, durability, energy-use, acoustics, suitability for specific uses, air purity, etc. The most recent version of GARM [2] shows how use can be made of existing ISO standards for requirement definitions for buildings (ISO 6241 and ISO 6242). These standards have to be reworked a little bit and formulated in a formal language to allow their use for data-exchange in computer-interpretable format.

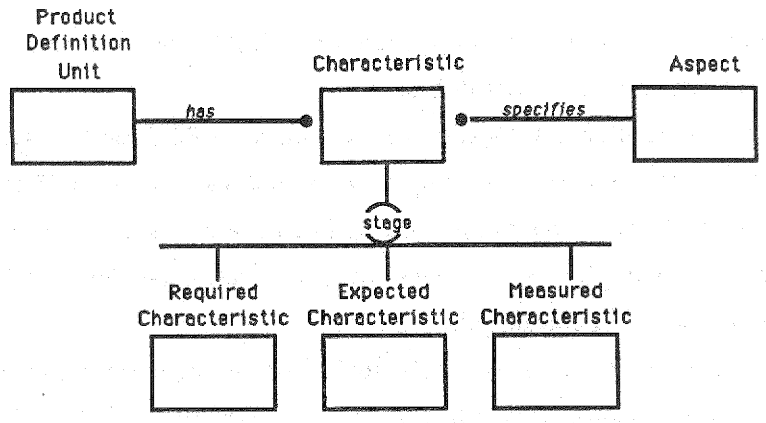


Fig.3. A Product Definition Unit has zero, one or many Characteristics, which are specified by an aspect. Three sub-types of Characteristics are defined in the GARM, based on the life-cycle stage: required, expected and measured characteristics. Expected characteristics result from analysis an simulation; measured characteristics will be available when the product physically exists.

Characteristics of a Building or Building-component cannot be given without paying attention to the environment of the Building (location, orientation, use, etc.). This environment is included by means of the entity Agent. A list of agents relevant to Building performance is also given in ISO 6241. This list is however not detailed enough for practical data-definition and -exchange. Extensions of this standard are required.

The products life-cycle can be modelled by applying a stage-discriminator to the PDU-entity. A discriminator is used within data-modelling techniques to define sub-types of an entity. GARM recognises seven fundamental stages in the products life-cycle. The following sub-types of the PDU represent the product in each stage:

Stage	PDU-subtype
As Required	Functional Unit
As Designed	Technical Solution
As Planned	Planned Unit
As Built	Physical Unit
As Used	Operational Unit
As Altered	Alteration Unit
As Demolished	Demolition Unit

Specialisation in GARM can be modelled by defining sub-types of a PDU using a classification technique. First, PDU's are sub-divided into four major classes of AEC product-types: Buildings, Plants, Ships, and Civil works. Then it is possible to choose one of several optional product-classification techniques, such as CI/Sfb, BIC, BSAB or ISO6241. Each classification defines broad classes of products, and specialises them to a certain level of detail. The classification techniques mentioned here tend to classify building-systems or

-elements based on their function. Therefore GARM handles them as an aid to define subtypes of Functional Units, not PDU's.

Decomposition in GARM is not pre-defined. A PDU can be a system, a sub-system, a component, a part, a feature[1], a space, or a joint. How all these PDU's are related to each other, or are decomposed, can be modelled by the user (the designer/architect). Since this is part of the design-process, it is one of the principles where Functional Units and Technical Solutions play an important role.

A Functional Unit is the "collector" of all the requirements for the PDU. It can be a design-problem (something to be solved) or a product to be obtained. The "answer" to this problem or the product that fulfils our requirements is represented by the Technical Solution. A Technical Solution has characteristics, which can be compared with the original requirements. It is possible to have zero, one or more Technical Solutions for one Functional Unit. If no Technical Solution can be found, it is clear that the requirements of the Functional Unit have to be changed. If there are several solutions possible, we have to select one. The other ones can be regarded as alternatives or will be rejected.

This principle allows us to proceed in a systematic way with the design process; the fact that several alternatives can be stored as part of the product model, and can be compared via product analysis, supports the designer to make the right choise. Analysis results and decisions can also be recorded with the General AEC reference model.

If a design-problem is very complex, the designer will usually solve it by dividing into a (structured) set of smaller design-problems. The "divide-and-conquer" strategy is typical for most design-processes. This is reflected by the possibility to decompose a Technical Solution into a structured set of Functional Units. As a result, the product-structure will be described as a tree. The principle developed in GARM is also able to support other design-strategies, such as operations research methods.

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[1] A feature is an area of interest on the surface of a part, for instance a pocket, a blend, a through-hole, or a slot.

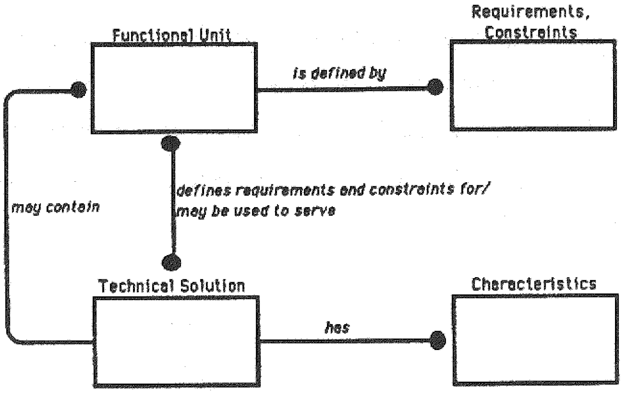

Fig.4. A Functional Unit is defined by required characteristics. A Technical Solution has expected characteristics. It is possible to find zero, one or many Technical Solutions for a Functional Unit. Only one of them will eventually be selected. A Technical Solution can be decomposed again into a set of Functional Units.

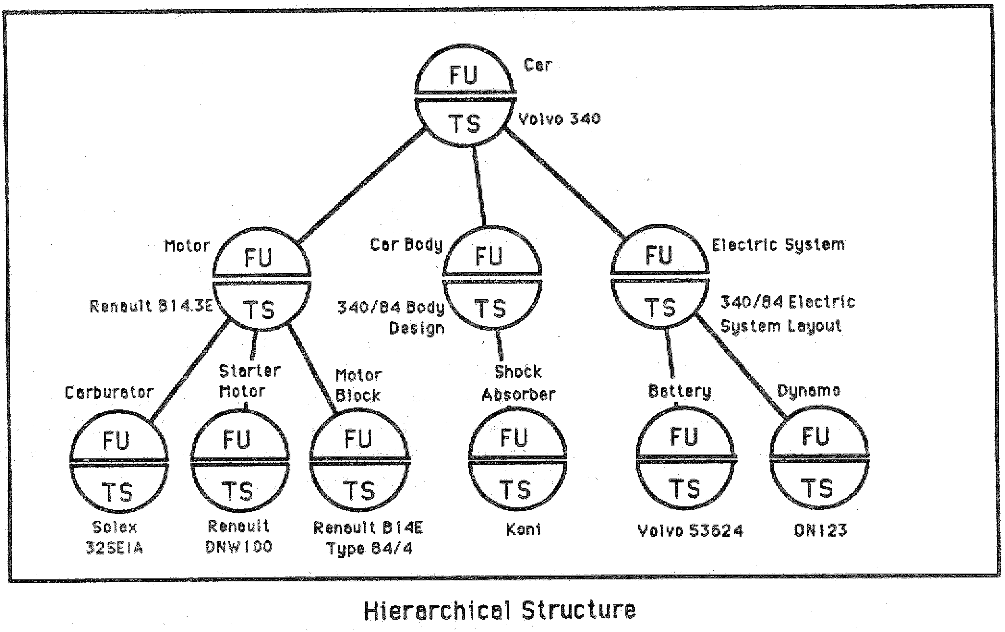

Fig.5. Example of the decomposition of a car. The car and each of its components is represented by a Functional Unit (FU) and a Technical Solution (TS) in the design stage. It is possible to use existing Technical Solutions, for instance ones that are offered by other manufacturers.

A tree-like product-structure is however not sufficient to model the "real world". The real world is a complex network of objects; everything may be related with anything else. These relations are modelled as a network between the Functional Units, reflecting the statement made before that a Technical Solution is a structured set of Functional Units. There is however one important rule built in the GARM: it is only allowed to model relations between Functional Units which belong to the same Technical Solution. This rule is built in to support the division of work into smaller pieces. Large AEC projects are not the work of one person; it is team-work. The product-model must therefore support the division of design-tasks. If the product would be regarded as one huge network, we would have big problems with maintaining the consistency of the model. Everyone should talk to everyone else to solve problems. Hierarchical structures are invented by humans to divide and conquer problems, but also to distribute tasks and responsibilities. This is what the hierarchical model reflects.

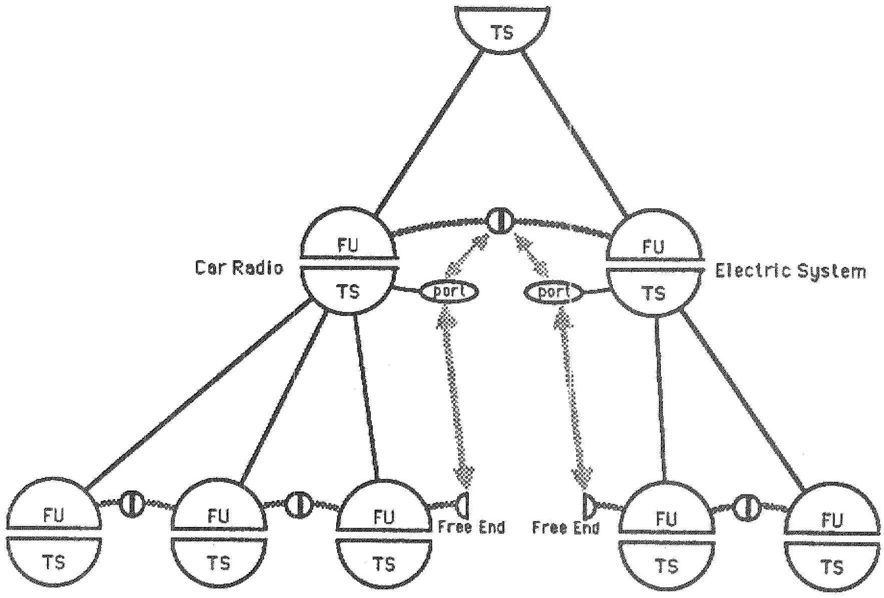

Fig.6. Functional Units which belong to different higher level Technical Solutions cannot be connected directly, but only through the functional network on the higher level. For this purpose we define Functional Units with Free Ends (Ends which are not connected by an interface). They belong to Ports of the higher level Technical Solution. These ports have to match with Ends of their corresponding Functional Units. An interface between two of these Ends connects automatically also the ports, including its lower level Free Ends.

Relations between Functional Units which belong to different Technical Solutions are to modelled on a higher level; see fig. 6. Functional Units which are supposed to be connected with other Functional Units in another network, have so-called free ends. These ends refer to one or more ports of the Technical Solution to which it belongs. And each port of a Technical Solution can be matched again with connected ends on the higher level network. An example: suppose we want to install a radio in a car. We buy a radio; we do not design and build it ourselves. The radio we buy can therefore be regarded as a Technical Solution. It has several ports: one to connect it with the antenna, two for the speakers, and one for the connection with the electric power supply. As a buyer of the radio, we are not interested in the internal structure of the radio; we are also not responsible for the connection of the ports with the components inside. But we are responsible for the connection of the ports of the radio with the ports of the electric power supply. The manufacturer of the radio will never know to which power supplies his radio will be connected; it is not his responsibility. Of course it is essential to agree about the ports, so that both systems can be connected. But those agreements are made on a higher level by the people who are responsible for the functioning of the whole product. These principles of Technical Solutions with ports and Functional Units with free or connected ends are built in the GARM, so that the real world can be modelled as realistic as possible, without having internal inconsistencies of the model resulting from the design-team problem.

GARM supports the use of various geometric representations. A distinction is made between two types of geometry: reference geometry and aspect-oriented geometry. Reference geometry is used as a means of communication between various partners in the design and production (or building) process. Aspect-oriented geometry is used for the simulation of the behaviour and/or analysis of the product. It is possible to use various geometric representations as reference geometry: wireframes, surface models, manifold boundary models and non-manifold boundary models. Reference geometry is used many situations for the definition of the functional network of systems (for instance installations and supporting structures). Therefore it is required to combine reference geometry with the functional network of the product, mentioned before. TNO has done several practical projects in the past in which the coupling of geometry and topology with the functional network gave problems. These problems were solved by the development of a "high-level" type of topology that can be used to integrate various representations of the product, and is also capable to interpret topology as a network. This principle is called Meta-topology. It will be included in version 1 of the standard. A description of meta-topology is given by Peter Willems [8].

Proof of concept

It is important that proposed models for a standard are implemented an tested in practice. TNO-IBBC has developed for this purpose the experimental product-modeller ProMod, which has an internal data-structure that is very close to the proposed concepts of the GARM. Several test-cases were modelled with ProMod. Three of them are worth while to mention here. The first is a model of a small office building (fig.7), which is used to integrate two types of geometric representations (an idealised model of the building using non-manifold topology, and a solid boundary representation), energy-calculations of the building, and the generation of bills of quantities. The model contains also functional information and can be used to select alternative Technical Solutions (for instance other walls if one of the rooms is given another function).

The second one is a more detailed model of a road-sign. Especially the steel structure of this sign is modelled into complete details, including bolt-holes and welded connections. Again an integration of idealised model and boundary model is made, including various levels of detail in the hierarchical tree. It was especially this model which showed us the importance of having a good structure of free ends of Functional Units and ports of Technical

Solutions, in order to model also the connections through various levels of the hierarchy. A FEM model for strength calculations was automatically generated form the augmented idealised model. Results from the calculation were included again in the product-model.

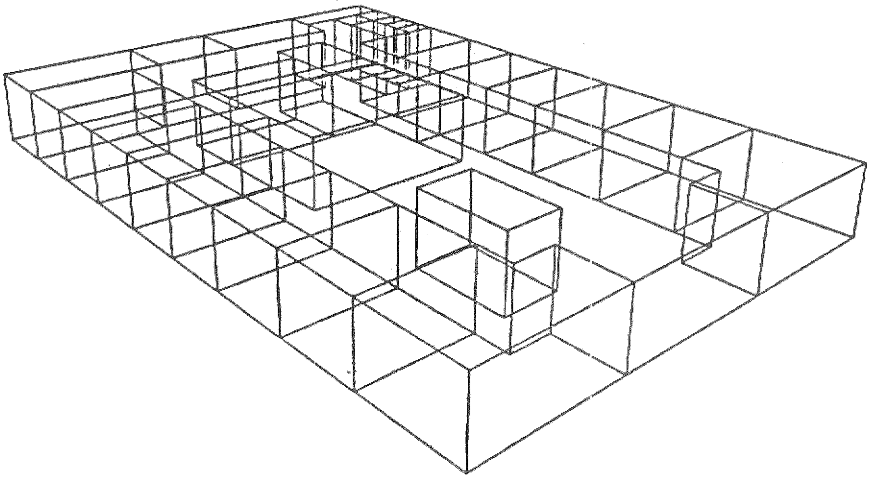

fig. 7. Model of a small office building. This idealised model with a non-manifold boundary representation is used for several applications, such as energy-calculations and bills of quantities It will also be used for the positioning of robots for computer-controlled construction.

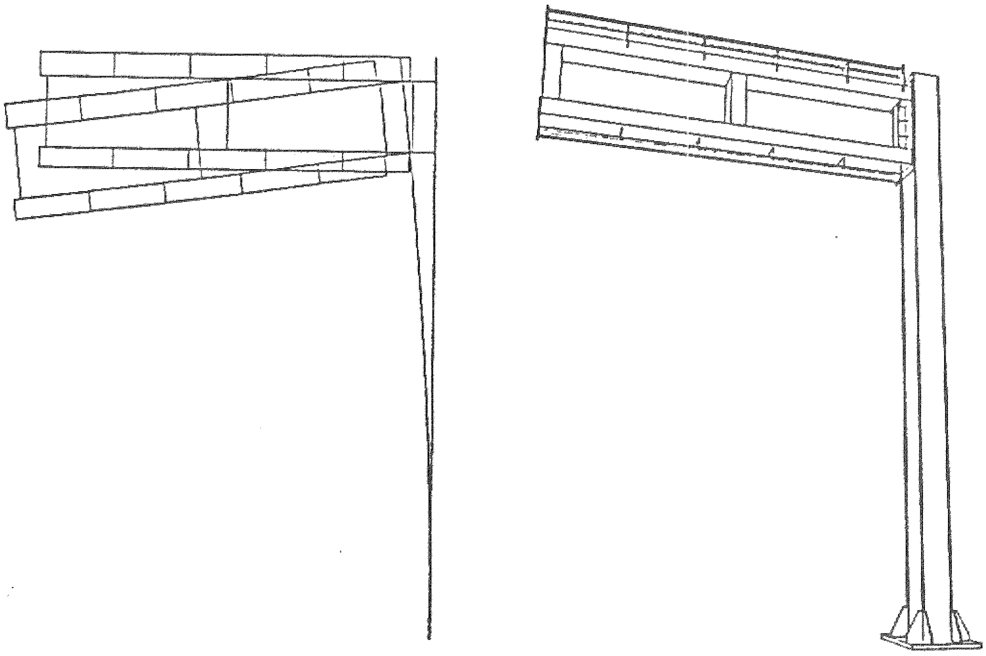

fig.8. A product model of a road sign is used for the automatic generation of a FEM model for strength analysis (left) and the the generation of a solid model (right).

The third example is the most complex one we have modelled so far. It is a complete and detailed model of concrete bridge (viaduct). The model is so large that it appeared to be impossible to generate one hidden line picture of it with our current system. The complete product model can be stored easily, however, since it is possible to reduce redundant data in a GARM model.

TNO-IBBC has done also several experiments with data-exchange using the STEP exchange format. Experimental STEP-translators were built for ProMod, Gradis (a Swiss digital terrain modeller), Calma, Autocad and MOSS (a road design modeller), so that information can be exchanged between these systems. TNO has also exchanged STEP-files containing solid models with the National Institute for Standards and Technology (NIST, the former NBS) in the US.

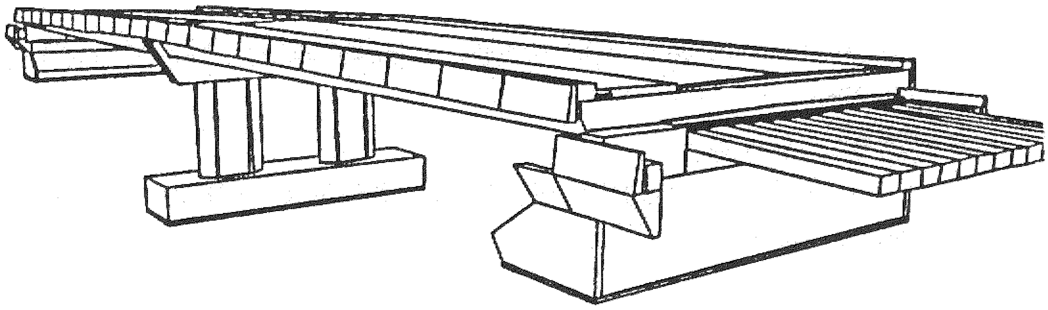

Fig. 9. This fly-over is modelled recently in full detail to integrate several applications using the concepts of GARM.

Summary

The ISO standard STEP will have a layered structure for general, industry-specific and product-specific data-structures, which can be extended with a fourth layer for non-STEP data-structures. The General AEC Reference Model (GARM) is intended as a general data reference-model for all AEC application areas, and will therefore be placed on the Industry-level of STEP. Specific product-oriented data models can be integrated with GARM by specialising the generic entities and adding product-specific data-structures. The concepts of GARM are tied to a new proposed planning model for the whole STEP development and show the interrelations of four major abstractions to be found in data-models, being specialisation, characterisation, decomposition and life-cycle.

The kernel of GARM is implemented at TNO-IBBC using the experimental product-modeller ProMod. Several interfaces with application-software were built, including (incomplete) STEP translators for several CAD-systems. These experiments will be extended and continued to provide a proof of concept for the proposed STEP standard.

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