# BUILDING REPRESENTATION FOR DESIGN INTEGRATION

**Albert A.J. Pols**
**Department of Civil Engineering**
**Delft University of Technology**
**Postbox 5048, 2600 GA Delft**
**the Netherlands**

## ABSTRACT

The present means of building representation, fall short in establishing a common modelling base for the various application specific analysis and simulation programs, describing building behavior and performance. A "generic", object-oriented, approach to product modelling allows multiple design representations to be described as different views of a common, gradually evolving, building product model. The productmodel provides the capability to generate, in successive design iterations, a coherent description of the form, structure and dimensions of the building. Associated technological and administrative data can be included in or associated with the productdescription. An information systems architecture portrays the integration environment for the modular organization of building data into a comprehensive information system, to effectively support design integration.

## INTRODUCTION

Design integration includes first of all integration within the design cycle: between design, engineering analysis and design evaluation. Integration of 3D modelling, 2D drafting and design analysis (calculations and simulations), a major focus of this paper, is essential in achieving this. Further integration of design, construction and building management covers not only the product development cycle but includes the entire product life cycle. Design integration is required to substantially improve the quality of building products, while lowering costs and reducing development time.

Recent concepts for integrated product development such as "Concurrent Engineering" or "Design to Product" underline the importance of incorporating the necessary feedbacks of experiences in construction and building management in the design process.
Product development covers the entire trajectory from specification of functional requirements to physical realization: from the client's brief and initial design concepts to the finished product. Simultaneous or concurrent, rather than merely sequential, development is a prerequisite for cost-effective design.
Assessments of "constructability" and "maintainability" are to be included in the design cycle. Simulation of manufacturing and assembly operations and building management strategies should become an integral part of design processes.

## MODELLING WITHOUT A COMMON MODELLING BASE

Current practice in building design and simulation is characterized by an increasingly wide range of independent, application specific, programs for design analysis and a disparate set of CAD systems for drafting, geometric modelling and visualization. Isolated application systems, with fragmented data models and separate filesystems, prevail.
The resultant information on the building product is dispersed over various drawings, technical performance calculations and simulations, bills of quantities or part lists, cost estimations and so forth.

The conventional or computerized 2D drawing, is a redundant but inherently incomplete and potentially ambiguous source of product and production information. Further computer processing of design data in analysis, frequently requires manual operations to extend or convert design data. The same data may also be entered over and over again in different applications.
The rapidly increasing range of application specific models for design analysis and building simulation (e.g. structural analysis, lighting, energy, quantity and cost estimation), demands a substantial increase in the capabilities for design coordination and building representation. The present means of building representation, fall short in establishing a common modelling base for the various application specific programs.

The model of the building object, as it evolves during the design process, provides the basis for building simulations, assessments of performance and costs, building code compliance checking and contract specifications. Processplanning in construction and building management also depend upon appropriate representations of the building object, as designed and as built. The participants in the building proces each partially describe the building to be designed from a certain point of view and with a particular purpose in mind. Various representations are used, in different applications and stages of development; building representational needs vary widely. The various partial representations nevertheless refer to one and the same building object; integration of the different "external views" into a unified model is required.
The wide variation in building representational needs underlines the vital importance, for more effective design coordination, of improvements in design data management and documentation.

The representation of the building product undergoes substantial changes as it moves through the development process, from initial concept to final product. Existing design coordination methods mainly rely upon 2D representation and "layering" techniques, supplemented by 3D visualisations or ad hoc interpretations. A "common" building product model is derived from various partial representations by "trial and error"-processes, due to the lack of formal models and methods for building representation.

Current capabilities in the management of building data can be drastically improved by the provision of a general model for the structuring of building data over the life cycle. A complete, consistent and unambiguous description of the common building object has to be created and maintained in any particular state of the design, to prevent inconsistencies in partial, application specific, representations.
Improved models and methods for building representation are indispensable to ensure data and design integrity across different scales and application areas and in various phases of development.

The elimination of unnecessary barriers in the sharing and exchange of building data between computer applications would establish basic conditions for integrated product development. A continuous information flow throughout the process of product development can be achieved, eliminating the need for manual conversions or multiple entry of the same data in different applications. Further improvements in the processes of generating, modifying and sharing product information are required to increase the capability for building modelling and information management.
Progressive integration of information flows between computer applications should ultimately lead to an Integrated Support Environment for design and construction with extensions to building management.

## APPLICATION SPECIFIC REPRESENTATION IN ENERGY ANALYSIS

The need for accurate and flexible design appraisal tools, which permit a more accurate prediction of energy consumption and performance characteristics of the building and its associated energy plant, is widely recognized. Indicative performance data, to allow preliminary assessments in the early design phases, such as U-values are subject to inaccuracies and may sometimes even be misleading.

Energy modelling requires basic geometrical description tools for the specification of orthogonal and non-orthogonal geometries, from which quantities such as planar angles, contained volumes and surface areas can be derived. Convection and radiation coefficients, air flows and so forth can then be derived from quantities, material specifications and their thermophysical properties. Homogeneous elements can be combined to form composite multi-layer systems such as windows, composed of glazing and thinfilm elements, walls, floors and roofs. Adaptive and combinatorial design problems in energy modelling range from such composite multi-layer systems to the combined optimalization of the building fabric and form, energy plant and operational management strategies.
A wide variety of geometric, construction and plant operations data is required, besides site location (orientation) and exposure information, including obstruction geometries.

The elementary conceptual buiding block in building description for energy modelling is the "zone". Zones can be combined to focus on groups or clusters of zones, characteristic building regions or the entire building. Editing facilities for zone description and modification are essential. Air flow, longwave radiation, solar penetration and so forth involve dynamic coupling between building zones.
Various combinations of zones and plant components can be included, as configurations, in the simulation. Connectivity between zones, between plant components and between zones and plant components has to be defined, relative to a coordinate system. In a phased simulation study, the findings from analyses of specific zones or clusters of zones can be successively incorporated in the overall buiding data set (Clarke 1985). Window and door geometry can be defined, relative to a local coordinate system, as "tiles" associated with the zone surfaces. This allows zone relocation without the need for window/door coordinate modification. The windowsystem can also be treated as one region.

A building is conceived, from a thermal point of view, as a complex network of thermal resistances and capacitances linking different regions and representing conductive, convective, radiative and heat storage processes. The manner in which this network is treated mathematically - some portion may be neglected, fixed values may be assigned or simplifying boundary condition assumptions may be made - will determine the flexibility of the modelling technique (Clarke 1985).

Energy modelling systems simulate the fundamental processes of conduction, convection, radiation exchange and heat storage at different levels of sophistication, to determine energy consumption and comfort levels.
The combined energy flowpaths inside and outside the building are determined by: the building form and fabric, site location and exposure, environmental conditions, plant configuration and layout, occupancy behaviour, control systems and operational management strategies. The flowpaths interact in a dynamic manner. Complex temporal and spatial relationships and time-varying thermophysical properties have to be accounted for. The combination of the various flowpaths determines the whole system balance.

In simplified models, for partial or preliminary assessment, energy flow paths may be approximated or entirely omitted by incorporating simplifying assumptions into the thermal network and/or solution scheme. Acceptable accuracy levels depend upon real world problem at hand and the modelling and design objectives at hand. Comprehensive models which are capable of simple model emulation, are more flexible in adapting to the quality of the available design information and the specific purpose of the application. A wide range of inputs may be allowed, varying from global and simplified to detailed. "Dynamic defaults" may be introduced in a comprehensive model to include flowpaths not explicitly adressed in the input data set (Clarke 1985). A modelling system which is capable of adapting to the information available in successive design phases and the specific purpose of the application, is most effective in the support of design.

## BUILDING REPRESENTATION AND DESIGN SUPPORT

Building modelling has to address the information needs of all participants in building processes over the entire lifecycle. Key objectives are:
the improvement of the processes for generating, manipulating and sharing product data and the reduction of consistency and datamanagement problems in building representation and design integration. A product life cycle approach, integrating object- and projectdata and the various processes in productdevelopment provides a general framework for building representation.

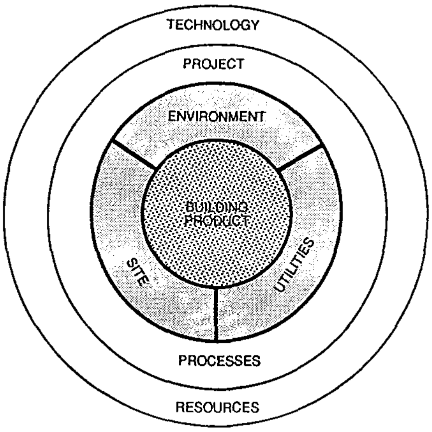

Figure 1 Building modelling; a comprehensive approach

An all-encompassing approach to building modelling includes, besides building objects, processes and projects, the description of a wide range of building utilities and services as well as the building site and its environment. This paper primarily focusses on the representation of a building as a spatial-physical unit to provide a common modelling base for various application specific analysis and simulation programs, describing building behavior and performance under varying conditions.

The model of the building-object as a final product evolves, in the course of the designproces, through a series of transformations. A structured set of functional specifications is first transformed into spatially structured functional areas and volumes. Concepts of form/shape and dimensions gradually materialise; the spatial and material structure of the building-object is further specified in conjunction with the representation of form and dimensions.
The design iterations include various computations and simulations that provide the necessary basis for continuous cost-performance estimates.
The iterative determination of form, dimensions and product-structure results in the specification of the final product, reflecting more detailed functional specifications and estimates of costs and expected performance on a variety of design criteria.
Repeated cost/quality trade-offs are involved.

Different parts or aspects of the design, have to be dealt with concurrently, at various levels of abstraction or detail. The need exists, even in the early design phases, for the preliminary detailing, analysis and evaluation of critical parts and assemblies, as these may strongly affect the functionality, visual appearance, technological feasibility and cost-performance of design concepts. One part or aspect of the design may be completely described with intricate detail while others concurrently exist at higher levels of abstraction, postponing further detailing until a later stage. The key to effective support is the ability to select the representation and tools in conformance with the tasks involved and to suppress unnecessary detail. A multilevel and multiphase approach to building representation is necessary (Pols 1988).

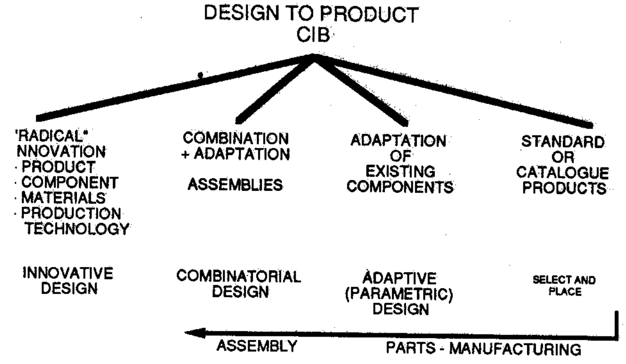

Figure 2 A range of Design modes

Effective support is required for a range of "design modes" with different degrees of innovation. Design ranges from "routine" application of standard components and the adaptation of previously designed solutions to more or less radical innovation (Encarnacao and Slechtendahl 1983).
Most design projects involve a combination of standard design procedures with "adaptive" and "combinatorial" design, rather than pure innovation in function, form, product structure, production technology or materials.

Routine application of standard components mainly requires the selection and placement, in a well-defined design context, of "catalogue products" with given technical and functional specifications.
Adaptive design involves the adaptation of previously designed solutions, that fulfill similar requirements, to specific client needs and diverging site conditions or technological and resource constraints. Design productivity can already be significantly improved by the provision of design "libraries" with facilities to support the searching and selection of standard components and capabilities for parametric design.

Combinatorial design generates a new combination of existing and/or new partial solutions and requires a series of interdependent adaptations at the level of components and assemblies or the building as a whole. The constituent components or subassemblies are treated as "configuration items". The support of combinatorial and innovative design still leaves much to be desired. Advanced methods for design analysis and evaluation are required to determine the feasibility of design options in combinatorial and innovative design.
Strong conceptual datamodelling capabilities are necessary to ensure design integrity (Pols 1991 b,c).

Building representational needs vary widely among participants in the building process, application areas and stages of design development. Models of varying complexity and accuracy are used in first order concept evalation and detailed design and analysis.
The representation requirements of structural analysis differ from lighting, HVAC-design or energy analysis. Within the application area of energy analysis, indicative or more detailed and accurate models, are used to simulate and predict energy consumption and comfort levels and to determine plant requirements and operational management strategies. Some application programs only require 2D geometry and material specifications or mass properties; others demand sophisticated 3D models and detailed design specifications.

Effective design support requires the capability of creating and manipulating a wide variety of partial, but mutually consistent, representations of the evolving building product, each serving specific purposes. Data and design integrity have to be maintained across different scales and application areas and in various phases of development (Pols 1991d). Integrated building product description demands full 3D modelling capabilities, supporting multiple representations, two-way associativity between the 3D model and drawings and concurrent access to geometry and associated non-geometrical data. Geometric associativity requirements include application specific representations such as finite element meshes and thermal networks.

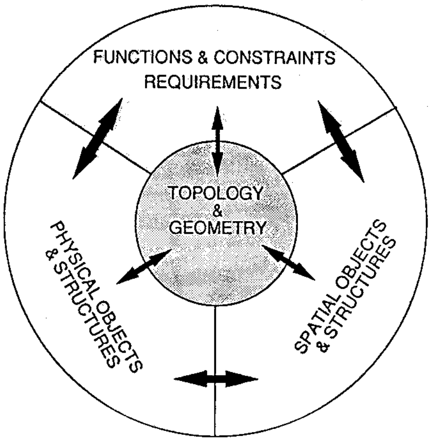

Figure 3 A building as a spatial-physical object

The need to deal with complex, interdependent, spatial and physical objects and structures, is the most characteristic feature of building modelling as a specific domain. This requires far more flexibility in combining spatial and non-spatial data than is currently provided by the most advanced geometric modelling systems, developed for industrial applications, and relational DBMS. Concurrent access to spatial and non-geometrical data is a necessity for integrated product development. Full associativity has to be maintained in a dynamic design environment.
The representation of a building as a spatial-physical object requires the capability to deal with spaces and their enclosure (solids with thickness or just contours and voids) and to define internal and external boundaries, central coordination lines etc.
A high degree of flexibility is required in handling spatial and physical objects and structures, seperately and in combination (space-material associations).

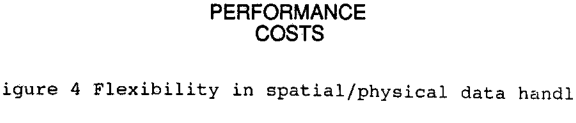

Figure 4 Flexibility in spatial/physical data handling

Initial concerns with the development of standards for the exchange of geometry and drawings among proprietary CAD-systems have broadened to include standards for the definition and exchange of all product data needed to describe a building over the lifecycle. The structuring of all lifecycle productdata among computer applications, on the basis of a generic "product model", is now becoming a new frontier in research and development and international standardisation. Such a "product model" would not only represent the product's topology and geometry but also capture technology data and financial-administative data over the entire product life cycle (Enkovaara 1988; Reed 1988). STEP, the designated "Standard for the Exchange of Productdata", is expected to replace less powerful and comprehensive graphical standards such as IGES (Slechtendahl 1988).

The standard reference model specifies the proposed datastructure and formats to be used by application programs of different participants in the building process. STEP will also provide the basis and methods for integrated distributed databases. STEP is to become a Draft International Standard in 1991; Version 1.0 was announced to be published this year (Wharthen 1991). Standardized datastructures and formats allow the sharing of product definition data without time consuming conversion or risks of data translation errors and provide fast and accurate communications among all product development functions.

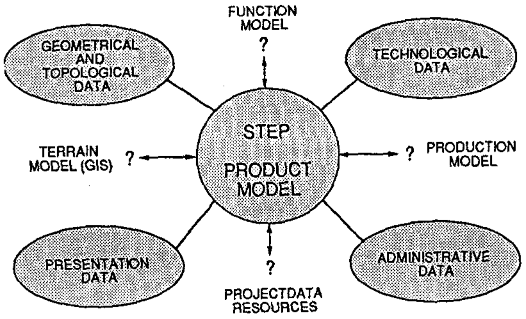

Figure 5 Purpose and scope of the STEP product model

The obviously ambitious initial STEP-proposals underline the need to further define the purpose and scope of a product model. A more comprehensive approach to building modelling is required to clarify the role of terrain data and project and resource data in this context. The allocation of modelling functions among requirements modelling, product modelling and production modelling also requires further investigation. Comprehensive standardization efforts in the field of productmodelling by ISO-STEP could revolutionize current practice.

## DATABASE SUPPORT AND KNOWLEDGE REPRESENTATION.

A generic conceptual datamodel for the description of the building as a composite spatial-physical object is required, to provide a basis for design analysis and evaluation. The underlying datamodel has to fulfill multiple demands, in different stages of product development and usage, from various users and applications. General criteria to be fulfilled by a generic datamodel for building representation include: validity, completeness, consistency and non-redundancy. The extent to which these requirements can be met, in the conceptual model and its implementation, depends upon the expressive capabilities of datamodels to formalise semantic meaning and integrity constraints, respectively upon the practical limitations of DMBS-technologies and knowledge representation techniques.

The introduction of semantic modelling techniques has substantially increased the capability to deal with more complex datastructures and to express the content, structure and semantic meaning of data (Brodie 1984.) Current databasetechnologies still lack the capability to deal with geometrical and non-geometrical data simultaneously, in complex datastructures (Pols 1991c). Design relationships and non-geometric data are to be associated with the geometry in dynamic data structures. Engineering applications require a fully associative database that combines geometry and attribute data in true engineering models. Specific requirements for engineering applications include: complex object support, version support, mechanisms to express general relationships and extended attribute domains. Besides the usual numerical and character string attributes, engineering applications may need support for lists, matrices and sets as attributes as well as "long fields"; unstructured fields of unlimited lenghth. (Encarnacao and Lockeman 1990). Integration of knowledge and databases and incorporation of multi-media applications in database technology is coming into reach. A suitable datamodel must support the characteristic properties of both processes and objects.

The object-oriented approach to data modelling and database design combines the advantages of semantic expressiveness and conceptual clarity with improved flexibility and maintainability of informationsystems development. The underlying conceptual data model closely corresponds with the language and working methods of a designer. Relatively independent and complete conceptual building blocks, information objects with real-world counterparts, combine data and processes or methods. Objects can be added, modified and deleted from a base model. The datastructures and programming techniques of object oriented systems would allow full integration of geometric and non-geometric data in a single database. Attribute data is united with geometric elements to fully describe their properties, roles and behaviours, forming "intelligent" and complete models of actual physical objects (Encarnacao and Lockeman 1990).

Knowledge representation, offers several abstraction mechanisms for the representation of objects and subobjects in abstraction hierarchies, that can be used for the structuring of building data. The abstraction mechanisms involved include: "classification", "generalization"/"specialization" and "aggregation"/"decomposition" of composite objects. "classes" or "types" of similar building components and assemblies can be defined, based upon common characteristics. Through specialization, the inverse of generalization, specific instances or occurrences from an object-class or type can be derived, with property inheritance. All instances of a given type share common attributes; exception handling has to be provided for. "Compound" or composite entities can be formed by aggregating the constituent components into a new entity. Decomposition is the inverse operation of aggregation. The "type"-concept provides a conceptual basis for adaptive and parametric design.
The "aggregate"-concept corresponds with combinatorial design of assemblies and their constituent components.

A wide range of user-defined relations among parts, subassemblies and assemblies and between building objects and processes can be described within a nested spatial coordinate system. The spatial and physical structure of the building is represented with "part of" /"contains"-relations and "connected to"-relations. Various other relationtypes are included in the conceptual modelling of building products and processes:
-"delimits"/"bounded by" (space-material associations);
-"precedes"/"succeeds" (structure of operations);
-"provides"/"utilizes resources" ( process-resource relations and supplier-resource relations).(Pols 1991a).

A "generic", object-oriented, approach to product modelling allows multiple design representations to be described as different views of a common, gradually evolving building product model. The subset of data used by an application corresponds with a view on the productmodel. The productmodel provides the capability to generate, from successive design inputs, a coherent description of the form, structure and dimensions of the building. Associated technological and administrative data can be included in or associated with the productdescription. Capabilities for concurrent access of geometry and non-geometric data

Building components and assemblies with their inherent topologies and geometries can be represented independently, as isolated physical objects and structures, by providing relative coordinate systems that allow orientation in a total design space. The complex shapes and structures involved in architectural form generation, location and massing studies or spatial layout design, conversely, can be represented without any explicit consideration of the building fabric. Space-material associativity is required to determine the space that is bounded by specific materials or retrieve the materials that enclose a certain space (Pols 1991b).

## FROM GEOMETRIC MODELLING TO PRODUCTMODELLING

Geometric modelling is an essential part of product definition. The representation of topology and geometry is a crucial factor in integrating design and drafting, engineering analysis, construction and building management. Geometric modelling capabilities determine to a large extent the degree of design integration that can be achieved in Computer Integrated Building ("CIB"). A geometric modeller which supports the entire design process must allow the interactive creation and modification of a full 3D model and maintain two-way associativity between the 3D model and 2D drawings (Pols 1991a).

Contrary to optimistic expectations, CAD has not become the central core of an integrated design system linking a variety of functions and applications. The terms CAD (Computer Aided DESIGN ) and CAD-CAM have been severely abused; the functionality of support for design and construction of Computer Aided DRAFTING has been limited. Other barriers to integration have been: incompatibilities in representation among the various modelling techniques and the lack of standardization in datastructures and exchange formats among proprietary systems.

Ad hoc linkages among drawing oriented CAD systems and applicationprograms (a.o. structural analysis, quantity and cost estimation, procesplanning, NC programming) have been established by transferring geometry, material specifications or mass properties and quantity take-offs. Integration at the application level is still in its infancy, but developments in datamodelling and database management systems (DMBS) have contributed to data integration and the emergence of a common user's interface (Pols 1991b). CAD has envolved from 2D drafting systems and partial 3D representations (wire frames and complex surfaces) to solid (volumetric) modelling techniques and combined surface-solid models.

The capabilities for 3D representation were initially restricted by the inherent limitations of wireframe and surface modelling: geometrical incompleteness (wireframes and surfaces) and ambiguity (wireframes). The initial, "geometry driven", solid modellers were too rigid to adequately support conceptual and preliminary design. Significant changes in these traditional, "static", solid modellers could not be made without entirely rebuilding the model. Much work has been carried out to combine the two major approaches to solid modelling, Constructive Solid Geometry (CSG) and Boundary Representation (B-rep), with their specific strengths and weaknesses, into a single unified geometric modelling system. Initial incompatibilities among the representations produced by these two solid modelling techniques, have only recently been resolved.

The formerly separate worlds of wireframe, surface and solid modelling have been combined and unified by providing a single mathematical foundation: non-uniform rational B-splines (NURBS). The new generation of advanced "hybrid" systems combines wireframe, surface, solid and parametric modelling functions into a comprehensive geometric modelling and drafting system. With capabilities for design support, full detailing, presentation, display and documentation to support the entire design process. Complex and accurate solids can be created from wireframe, surface and solid elements that share the NURBS representation. The NURBS representation also allows transitions from one technique to another.

The hybrid approach maintains both a boundary representation (containing precise definitions of the edges, faces and vertices of the model) and a history of the operations used to construct the model in the form of a CSG-tree. Boolean operators allow to combine, intersect and subtract the solid elements in global modifications. The record of the geometry construction process allows undo steps in the design sequence and promotes easy alteration of the model. The CSG tree can be displayed and nodes of the tree may be deleted, added, reordered or replaced. The speed of design modification is enhanced by only executing the appropriate section of the tree. Local changes to the model geometry can be made, as well as global modifications involved in cutting, joining and intersecting shapes. The NURBS representation makes the geometric model more malleable and responsive.

The solid model can be constructed by employing standard or user-defined design elements and form-features as well as basic construction tools; any geometric shape can be generated by revolving, extruding or sweeping contours and combining, subtracting or intersecting 3D models. The 3D model is used to create drawings by projection, to compute mass properties or to prepare various application specific representations, such as finite element meshes or thermal networks for energy simulation.

A new generation of object oriented solid modellers is now emerging, provided with:
- a more natural user interface, based on design elements and form features, and facilities for parametric, adaptive, design;
- full 3D modelling capacity with compatible solid model representations (constructive solid geometry, boundary representation and polyhedron representation);
- two-way associativity between 3D model and drawings.

All design data, from concept sketching through 3D modelling and drafting to visualization and documentation, can be developed in the same graphics environment and captured in a single geometric database.

Further extension of solid modellers into general-purpose product modelling systems poses difficult problems in terms of data structures and performance requirements. Requirements for the definition and manipulation of complex geometric objects, that are linked like networks, differ widely from "flat" non-geometric datastructures. The capability to incorporate a wider range of technological, financial-administrative and organizational data, required for life cycle product representation, of a geometric modelling system is fundamentally limited (Pols 1991a). The geometric data modelling systems cannot be extended to include additional non-geometrical data without penalties in performance and maintainability. Linkages between geometric modellers and relational database management systems can be established to fully utilize existing database technologies. Material specifications and tolerances can be directly associated with the geometry. Most of the non-geometrical productdata will have to be stored and retrieveved from other application oriented databases. Queries for general design management data - like the status of parts, version releases or designers involved - have to be supported.

The basic conditions for data integration also improve gradually by continuing progress in the development of international standards for the exchange of geometry and technical drawings among different CAD-systems and between CAD and other application areas. Recent standardization efforts in CAD-I should allow the transfer of solids among various proprietary systems (Slechtendahl 1988). Advanced commercial geometric modelling systems presently offer an interface based on IGES 4 with extended capabilities for exchanging fully dimensioned and detailed drawings, 3D wireframe and surface models and 3 D solid models in CSG and boundary representation as well as polyhedral solids.

have to be provided. Two-way associativity between 2D drawings and the 3D productmodel is to be maintained.

An object oriented approach that uses design elements and form features as building blocks, rather than just geometric primitives, naturally corresponds with the designer's language and thinking patterns. Design elements and formfeatures simplify geometry creation, facilitate design modifications and provide a description that is better adapted to assessments of constructability and maintainability.

## A GENERIC APPROACH TO PRODUCT MODELLING

Basic objectives in the development of a computer internal product model are: to provide the capability to represent all product characteristics over the life cycle and to create basic conditions for data exchange among computer applications and database integration. A building product model should be able to capture all kinds of building data to be used in design, construction and building management. Building modeling involves the representation of buildings as a complex spatial-physical object and the transformation of the building object, into building operations during construction and in the usage phase. An integrated approach to building product and process modelling is required.

An abstraction hierarchy, ranging from single parts or components to the building as a whole, provides the conceptual framework for a "generic" productmodel that captures the invariances in building representation. The productmodel includes interrelated spatial and physical entities, arranged in an object hierarchy, extending from individual components to assemblies and the building as a whole. Any building object can be described, at any state of product development, as an assembly of spatial and physical components. The product model contains a description of 3D topology/geometry, materials used and their physical properties as well as additional technological, financial-administrative and organizational information for diverse applications. Presentation data, needed to generate 3D visualizations, 2D displays and dimensioned technical drawings is included as well. The conceptual data model is a logical structure on the semantic level that can be implemented by several programmimg and database techniques. The applications refer to a subschema or view rather than the general conceptual schema itself.

A multilevel and multiphase approach to building representation enables the designer to deal with different parts or aspects of the design concurrently at various levels of abstraction or detail and allows integration of object, process and projectdata. Sub-assemblies can be distinguished to represent assemblies of assemblies, at multiple levels of abstraction or in different phases of product development. Assemblies and/or sub-assemblies may be associated with sub-projects or specific tasks in design or construction.

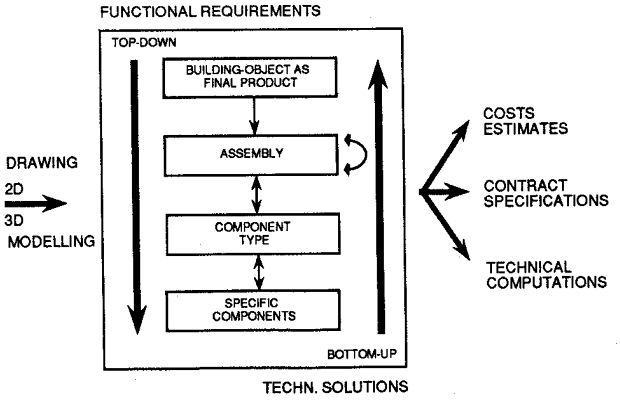

Figure 6 A generic product model

The productmodel gradually evolves in a series of design iterations, involving refinements of initial functional and technical specifications, the generation of alternatives and design analysis and evaluation. Each phase of the design process yields results which describe the design object from a phase-specific view. General productmodelling functions include : functional and technical specification, the determination of form and productstructure, dimensioning, cost and performance estimation and the transformation of design options into building operations for design analysis and evaluation.

The product model is continually supplied with new design information and updated with the results of application specific analyses and evalations. Design inputs may include 2D sketches and drawings, 3D conceptualizations and additional information such as specifications of materials and tolerances. Application programs operating on the productmodel extract and produce product information; the model is modified and refined in the meantime. The product model provides product data to application programs, allowing data to be shared and exchanged among applications. The product model is "tapped" by users, extracting product information in the form most suitable for specific views and applications. The results of the analyses may be included in the product description. Several design alternatives and versions may be included in the productdescription, for a choice to be made at a later stage. Representations, revisions and alternatives may be organized in hierarchy of versions.

The product description is created dynamically; application specific programs for technical calculation, building performance simulation analysis and cost estimation operate on the product model and further extend it. Design iterations, generate alternative technical solutions for analysis and evaluation. "Top-down" and "bottom-up" approaches can be effectively combined within an overall top-down design strategy, switching back and forth from functional requirements to technical solutions. Cost estimations and technical performance analyses (calculations and simulations) provide support for continuous cost-quality trade-offs. The product specification at the component-level is not limited to dimensions and materialproperties and tolerances, but may also include assembly- and manufacturing-"recipes" (activities and resources, times and costs) and maintenance expectations.

All applications work concurrently with the same product model, stored in a single distributed database, ensuring that all changes are communicated to each link in the product development chain. Database query and report generation capabilities effectively transfer product information to applications. Drawings and documents are generated, on user demand, as "displays" from the product model. The availability of a complete, consistent and unambiguous representation of the building object, in its intermediate stages and as a final product, is of vital importance for the control of design changes and preservation of design integrity. Varying combinations of input data are used in the different application specific analysis programs. Each application uses a particular combination of input data, while different applications may use the same inputdata.

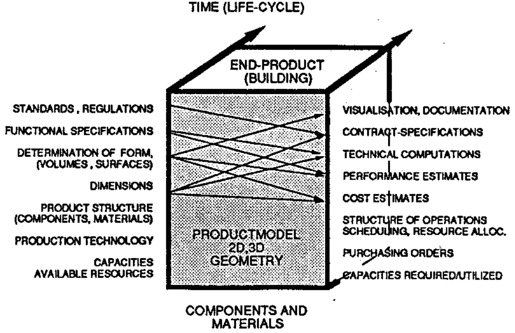

Figure 7 Integrated product development

An integrated approach to product and process modelling is required to practically transform a generic or standard reference model into an appropriate model of a particular building. The reference model is a "meta"-model that describes how information about products can be captured in a neutral, generally applicable datastructure and format. The representation of a particular building product involves stepwise refinement of the "meta"-model by adding detail and auxiliary specifications. Bottom up and top down approaches are applied iteratively. The model must be managed dynamically because the possibility to modify, refine and extend the data structure is indispensable for practical application.

## TOWARDS A BUILDING INFORMATIONSYSTEMS ARCHITECTURE

Current international efforts to develop a standard productmodel for the definition and exchange of product data (ISO/STEP), mainly specify what kind of information is needed to describe buildings over the lifecycle and how such information is to be structured. The specification of a common product model, however, is only the first step towards successful implementation of the information architecture and wide spread application in design and construction.
The development of an appropriate informationsystems architecture for building modelling, which includes but is not limited to productmodelling, is a necessary complement to the specification of a conceptual information architecture for the structuring of building productdata. The major challenge is not only to structure and integrate data into a product model but to provide a sufficiently wide range of product modelling functions and powerful tools to create an appropriate model of a particular building.

Design to production requires effective integration, within a famework of projectmanagement, of functional and geometric modelling, productmodelling and production modelling. A clear allocation of modelling functions is required. Product modelling, in the most comprehensive view, would include functional, spatial and physical modelling and incorporate the technological and administrative data to generate process plans for manufacturing and assembly. The product model is considered to be the integrative "core" of building modelling.
The capability to interactively determine the form, structure and dimensions of the building product and to incorporate the associated technological data is most essential. Incorporation of peripheral modelling functions and additional administrative and presentation data may result in decreased functionality and performance of the functions that are considered as the "integrative core".

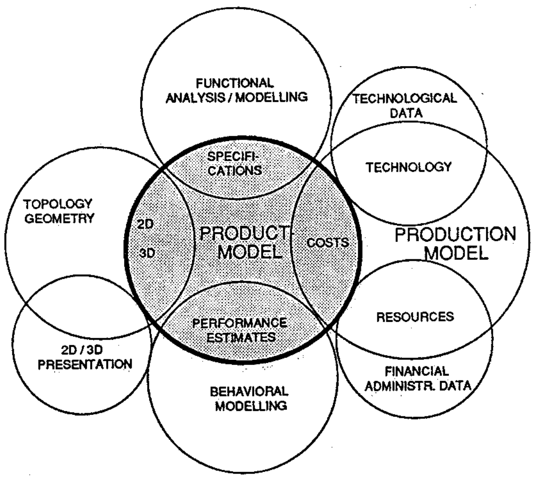

Figure 8 Information Systems Architecture

Most integration concepts assume a single product database to support all target applications over the life cycle. The information systems architecture for building modelling will be modular and distributed rather than centralized. Modularity is indispensable to allow the gradual implementation and extension of the informationsystem and to ensure data integrity and effective maintenance of the database (Pols 1991b).

The total building information system is conceived to be composed of integrated modular units that correspond to functional tasks and can be implemented and adaptated separately. In the future working environment, the product database will be physically be distributed over different locations in computer networks. The possible information systems architecture portrays the integration environment for the modular organization of building data into a comprehensive information system, to effectively support design integration. Productmodelling, to be implementable in practice, demands a sufficiently broad range of capabilities for modelling, display and documentation, embedded in an Integrated Support Environment.

## REFERENCES

Pols, A.A.J. 1988." A Generic Approach to the Modelling of Buildings, Focussing on the representation of Product Structure". In Proceedings CIB- W74+W78 Seminar "Conceptual Modelling of Buildings". (Lund, Sweden, october 1988) Publication 129. The Swedish Building Centre, Solna.

Encarnacao, J. and E.G. Slechtendahl. 1983. Computer Aided Design. Springer Verlag, Heidelberg.

Pols, A.A.J. 1991a."Building Representation in Design: an Integrated Approach to Building Product and Process Modelling". In Proceedings of the 3th International Symposium on Computer Aided Design in Architecture and Civil Engineering ( Barcelona, Spain, april 1991). Institut de Technologia de la Construccio de Cataluna.

Pols, A.A.J. 1991b. "Towards an Integrated Support Environment for CIC; Design to Construction of building assemblies". In Proceedings of the CIB-Seminar on Computer Integrated Construction ( Tokyo, Japan, september 1990). To be published by Elsevier Science Publishers, Amsterdam.

Reed, K. 1988. "Productmodelling of Buildings for Data Exchange Standards". In Proceedings CIB-W74+W78 Seminar "Conceptual Modelling of Buildings".

Enkovaara,E., M. Salmi and A. Sarja. 1988.
RATAS project, Computer Aided Design for Construction. Building Book Ltd, Helsinki, 1988.

Slechtendahl, E.G.(ed.). 1988. CAD Data Transfer for Solid Models. ESPRIT Research Reports, Vol. 3, CAD*I. Springer-Verlag, Heidelberg.

Pols, A.A.J. 1991c. "Building representation; an integrated approach to building modelling".
In Proceedings of the Second International Workshop on Computer Building Representation for Integration.
( Aix-les-Bains, France, june 1991). To be published by LESO, Ecole Polytechnique Federale de Lausanne.

Clarke J.A. 1985. Energy simulation in building design. Adam Hilger Ltd, Bristol and Boston.

Brodie, M.L., J. Mylopoulos, J.W Schmidt. 1984.
On Conceptual Modelling. Springer Verlag, Heidelberg.

Pols, A.A.J. 1991d. " Conceptual modelling of building assemblies; bridging the gap between data integrity and design integrity". In Proceedings of the CIB-Seminar "The Computer Integrated Future". (Eindhoven, the Netherlands, 16-17 september 1991. Elsevier Science Publishers, Amsterdam.

Wharten B.D. ed. 1991. Product Data International. Wharten Communications, Cardiff-by-the-Sea, CA 92007

Encarnacao, J. and P.C. Lockeman, eds. 1989. Engineering Databases. Springer Verlag, Heidelberg.