Conceptual modelling of building assemblies; bridging the gap between building data and design integrity.

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Abstract

Improved models and methods for building representation are needed for more effective support of design integrity checking and control. 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 product model provides the capability to generate, in successive design iterations, a coherent description of the form, structure and dimensions of the building and its assemblies and components. Associated technological and administrative data can be included in or associated with the productdescription.

1. Introduction

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 and the use of spacing grids, supplemented by 3D visualisations or ad hoc interpretations of intermediate results. 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 and design integrity control.

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 (e.g. structural analysis, lighting, energy, quantity and cost estimation), demands a substantial increase in the capabilities for design coordination and building representation.

Tools for achieving and maintaining design integrity in current practice range from rules of thumb and first order visual assessments of design concepts to the usage of advanced methods and models for detailed and rigourous design analysis and evaluation. Improved models and methods for building representation are indispensable to facilitate the control of design integrity across different scales and application areas and in various phases of development. Database integrity can be considered as a necessary but not sufficient condition for effective control of design integrity.

A sufficiently 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. Current capabilities in the management of building data can be drastically improved by a generic approach to the structuring of building data over the life cycle. Unnecessary barriers in the sharing and exchange of building data between computer applications have to be eliminated to establish more favorable conditions for design integrity control. 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 (as a source of misrepresentations and errors).

2. Building representation and design support

The model of the building-object as a final product evolves, in the course of the designprocess, 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. Building assemblies (e.g. foundation, structure, internal and external enclosures and installations) and components are gradually specified in detail. 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 according to 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.

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 key to effective support is the ability to select the representations and tools in conformance with the tasks involved and to suppress unnecessary detail in the description of the building product as a complex structured object. A multilevel and multiphase approach to building representation is necessary (Pols 1990).

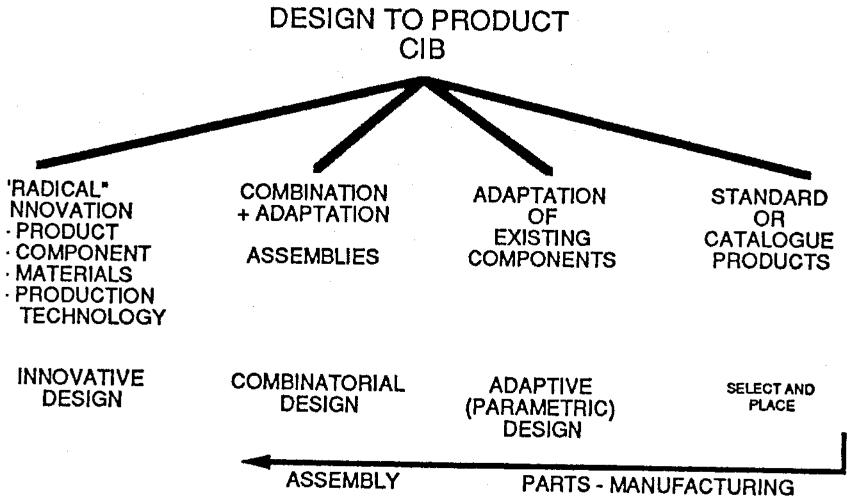

Figure 1 A range of Design modes

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).

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 1991a). 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 also include application specific representations such as finite element meshes and thermal networks.

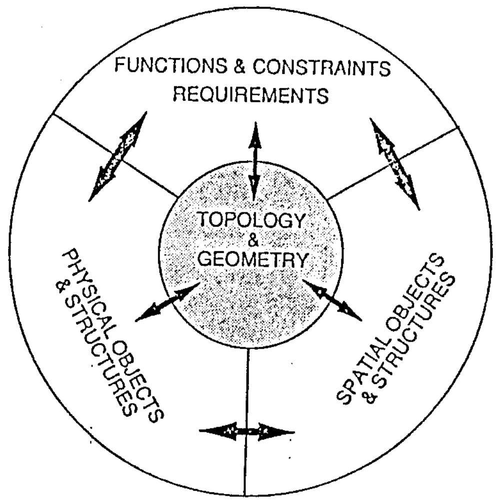

Figure 2 A building as a spatial-physical object

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 rrently provided by the most advanced geometric modelling systems, developed for industrial applications, and DBMS which primarily support administrative applications. Concurrent access to spatial and non-geometrical data is indispensable for integrated product development. Associativity has to be maintained in a dynamic design environment.

The representation of a building as spatial-physical objects 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).

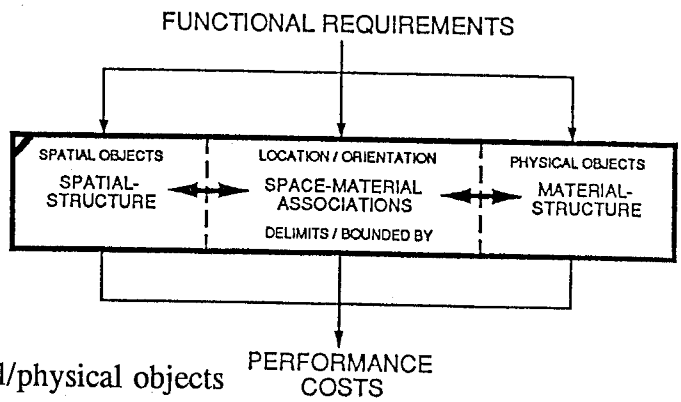

Figure 3 Flexibility in the representation of spatial/physical objects

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

3. Developments in geometric modelling

The representation of topology and geometry is a crucial factor in integrating design and drafting, engineering analysis, construction and building management. Geometric modelling is an essential part of product definition. 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 1991b). Geometric modelling capabilities determine to a large extent the degree of design integration that can be achieved in Computer Integrated Building ("CIB").

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 functionality of support for design and construction of drawing oriented CAD systems has been rather limited. Contrary to optimistic expectations, CAD has not become the central core of an integrated design system linking a variety of functions and applications. Other barriers to integration, apart from limited functionality, have been: incompatibilities in representation among the various modelling techniques and the lack of standardization in datastructures and exchange formats among proprietary systems.

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 solid model can be constructed by employing standard or user-defined design elements and form- features as well as basic geometry construction tools. The 3D model can be 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 as well.

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). The structuring of all lifecycle productdata among computer applications, on the basis of a generic "product model", has become 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). 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.

4. A generic approach to product modelling

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.

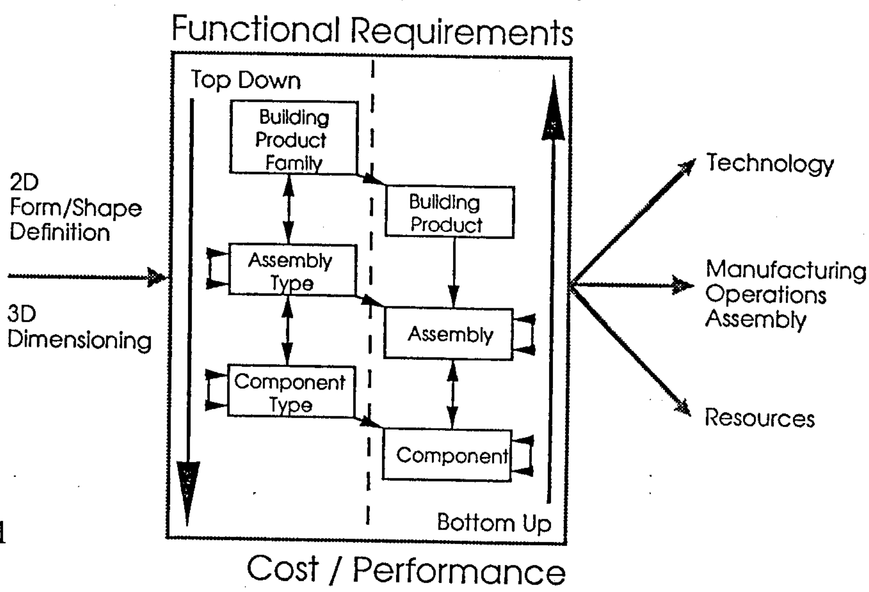

Figure 4. A generic product model

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.

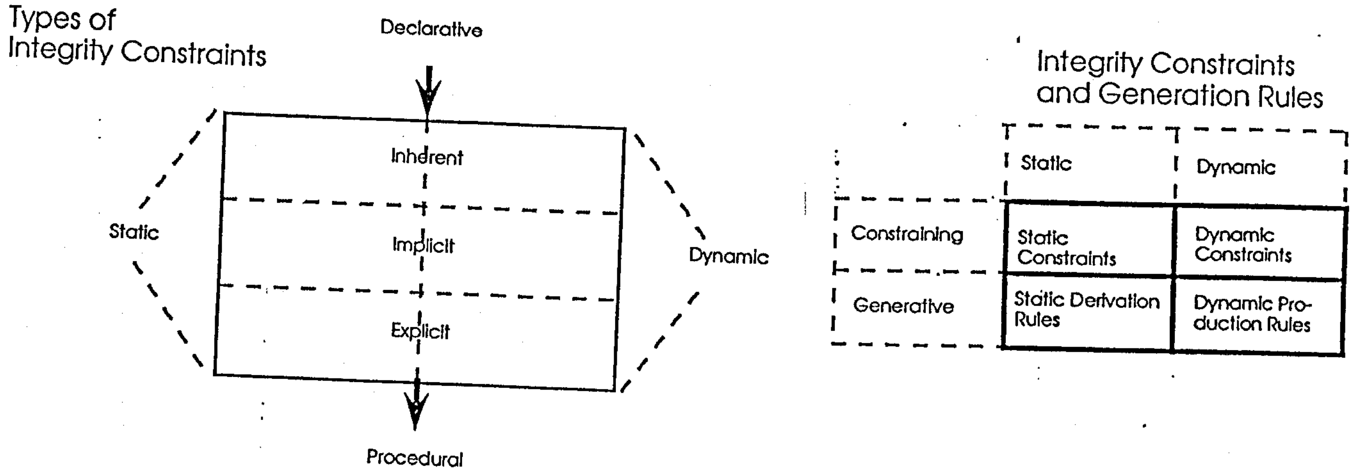

Figure 6. Types of integrity constraints

Integrity constraints may range from "uniqueness" requirements, constraints on atttribute values (type and domain), attribute structural constraints (cardinality, total/partial participation) to constraints on specialization/ generalization (joint/disjoint and total/partial). In order to have the DBMS enforce consistency , integrity constraints in existing DBMS must be specified a priori during database design. Only the most elementary constraints are currently supported by existing dBMS. Automatically enforced integrity constraints may prevent inconsistencies such as zero length of structural members or isolated nodes in geometry definition and allow the specification of allowable beam spacings or spanlenghts.

The introduction of semantic modelling techniques has significantly 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 (Encarnacao and Lockeman 1990). Integration of knowledge and databases and incorporation of multi-media applications in database technology is coming into reach. An 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/instantiation", "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). Special spatial semantics, such as "spatial inclusion/enclosure", "is-next-to" or "above" and "below", may be used to specify spatial relationships. Time dimensions such as intervals or duration, discrete points (e.g. design versions or milestones) and abstract temporal relationships (e.g. "before", "after", "during") can be included in the datamodel as well (Dayal and Smith, 1986).

6. Summary

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 and its assembies and components. Associated technological and administrative data can be included in or associated with the productdescription. Capabilities for concurrent access of geometry and non-geometric data have to be provided. Two-way associativity between 2D drawings and the 3D productmodel is to be maintained.

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