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A Global Model for Building-Project Information: Analysis of Conceptual Structures

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

Abstract

The development of a consensus model for building-project information requires a precise description of the meaning of the information to be maintained. This report presents an analysis of the conceptual structures that are available to specify that meaning using a proposed "global model" as an example. The model is currently under development by the Architecture, Engineering, and Construction (AEC) Committee of the Initial Graphics Exchange Specification (IGES) / Product Data Exchange Specification (PDES) Organization.

The key conclusion of this analysis is that a core semantic vocabulary is needed. This core vocabulary derives from how meaning is expressed without regard for specific domains of information. Preliminary elements of such a core vocabulary are defined. Further, a means by which that core is extended to add necessary domain-specific semantics is presented. The analysis has identified those aspects of developing a global model for building-project information that should proceed in the context of a broad interdisciplinary effort to represent information and those that require extensive technical input from the building industry.

Keywords: building data; building information; conceptual modeling; data modeling; information modeling; semantic modeling

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1. Introduction

1.1 Background

There has been considerable interest in recent years in the possibility of developing a global conceptual model for building-project information. This interest has intensified with the advent of semantic modeling techniques in both the fields of database management and artificial intelligence [1,2]. Application of such techniques presents the possibility of encoding building-project information in an accessible and meaningful form for all participants in the building process over the entire life-cycle of a building.

The Initial Graphics Exchange Specification (IGES) / Product Data Exchange Specification (PDES) Organization is developing a "global model"[1] for building-project information within its Architecture, Engineering, and Construction (AEC) Committee [3]. Other conceptual models are also being developed in conjunction with the IGES/PDES AEC Committee, however, reference to the AEC Model in this report refers to the "global model." This AEC Model is a first step toward the long term goal of a global building-project information model. It is being developed to represent a finite time in a building's life-cycle as a means of limiting the scope of the problems encountered in establishing industry-wide specifications for such a large domain of information.

1.2 Terminology

The central focus of this report is the specification of meaning (i.e., semantics) in the development of an information system at the logical level. It represents a synthesis of approaches to this topic from a number of disciplines including database management, artificial intelligence, and linguistics as well as from the building industry. Terminology both within and between these disciplines is extremely varied. For example, what has been described as a conceptual model by the IGES/PDES AEC Committee is often referred to in the database literature as a conceptual schema. The term "data model" in this context identifies a formal approach to specifying a conceptual schema. This report adopts the use of the word "model" as used by the AEC Committee and uses it interchangably with the term schema. The distinction between model (i.e., schema) and data model is maintained.

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1 This model has recently been renamed the "Building Systems Model" (March 1988).

Throughout this report, terminology has been adopted that is eclectic among the disciplines listed above. Therefore, definitions are given as terms are encountered. The terms have been chosen to facilitate the discussion of the topics being presented rather than to endorse any given formal approach to conceptual modeling.

1.3 Purpose and Organization

This report addresses issues of knowledge representation and semantic modeling in the context of the preliminary AEC Model for building-project information. Of particular importance is the initiation of a discussion on the process by which such a model is developed and the conceptual structures that are chosen to represent information during that process.

After the introductory remarks of this section, Section 2 presents an overview of the basic conceptual structures used in the current AEC Model. The specification of ideas is described as both the identification of largely domain specific concepts and the selection of more generic relationships that serve to establish the logical connections between concepts. The relationships of the AEC Model are then discussed in terms of categories based on the grammatical constructions used in their specification.

Several alternative representations for specifying ideas are presented in Section 3. They include symmetric, relational, and graphic representations. Conversion from one form to the other is discussed. Relationship types reflecting the categories identified in Section 2 are then defined. The use of relationship types is suggested as a means by which a systematic approach to the specification of ideas can be established.

Section 4 returns to the topic of identifying concepts. Their development through specification of ideas is outlined. The discussion then proceeds to the identification and development of constructs formed by a group of hierarchically related ideas. The section ends with a discussion of concepts that serve as prototypes for other concepts. Examples from the current AEC Model are used extensively.

Section 5 presents a summary which reviews the conceptual model development process. Conclusions include recommending the use of a systematic approach to the specification of the conceptual structures. In particular, the use of relationship types in defining relationships and the explicit identification of constructs and prototypes that are central to the overall organization of building information are advocated. The final sections present an overview of the schema development process and the utility of a core conceptual vocabulary that serves as the foundation for domain specific information models such as those being developed for the building industry.

2. Analysis of Conceptual Structures

2.1 Overview

The AEC Model has served as a basis for prototype information system implementations which have been used as testbeds for investigating topics of knowledge representation and schema development. Specifically, a frame-based information system has been implemented using a knowledge-base development environment on a Lisp machine and a predicate logic based relational information system has been implemented in Prolog with an emphasis on user interface characteristics. The latter system was used to explore desirable characteristics of a schema development environment that would be of assistance in the specification of conceptual structures. A discussion of the preliminary AEC Model follows based on observations made during the implementation of these testbed systems.

2.1.1 Concepts

"Concepts" in the context of this report represent a class of uniquely identifiable things, events, or notions. Examples include the central concept of a building project in the case of the AEC Model and the building and site that are parts of a building project. Within the field of conceptual modeling, concepts are variously described as concepts [4,5], object classes [1], or entity types [6,7]. Each of these terms is meant to indicate that a concept does not represent a particular building for example, but rather represents a class of which there can be many instances, in this case many buildings.[1]

The preliminary AEC Model contains over 500 concepts, many of which are domain specific. That is, most of the concepts have been specified in the early stages of the AEC Model development for the explicit purpose of communicating information about buildings. No attempt has been made in this report to evaluate the suitability of the concepts chosen or their ultimate usability in a global information model. This task falls clearly within the scope of the members of the AEC Committee and others within the AEC community who will select concepts based on the needs of the participant groups they represent. Rather, issues of knowledge representation that apply to these concepts as they have been defined and which would have essentially equal validity for other concepts are discussed in the sections which follow.

1 The IGES/PDES Organization has adopted the terminology of "entity" to represent a concept and "occurrence" to represent an instance of a concept.

2.1.2 Ideas

"Ideas" are composed of several concepts and a relationship that establishes a logical connection between those concepts. "Building has-part building-element" is an example of an idea.

2.1.3 Relationships

"Relationships" represent the logical connections between concepts in a conceptual model. In stating the idea that "building has-part building-element," one is stating that there exists a whole-to-part relationship between the concept "building" and the concept "building-element". Frequently in defining ideas, conceptual models make use of alternative ways of stating the idea when taking the perspective of one or the other concept. Therefore, "building has-part building-element" and "building-element part-of building" can be seen to be aspects of the same idea. These representations can be considered to be an obverse and inverse representation of the idea. What is emphasized in such representations is the role played by each of the concepts. The idea can be considered from the perspective of the building (the whole) or the building-element (the part) each of which leads to a slightly different statement of the relationship ("has-part" and "part-of" respectively).

2.1.3 Relations and Roles

A relationship can be specified most clearly in terms of a relation and its associated roles. A "relation" identifies the nature of the logical connection. A "role" is a link that can be used between a relation with which it is associated and a concept in forming an idea. A role identifies the function of the concept in the idea. (See also [8].)

The "has-part/part-of" relationship pair combines the "part" relation with other words that indicate the roles played by each concept in an idea. In the obverse representation of our example, the verb "has" in combination with part identifies the role of the whole as being primary ("building has-part building-element"). In the inverse representation, the preposition "of" identifies the role of the part as primary ("building-element part-of building"). Relationship pairs like "has-part/part-of" then are one means of conveying the semantics of both a relation and associated roles of the concepts in an idea.

Often, however, the representation of the relationship from the perspective of one concept is quite obvious, but from the perspective of the other concept seems forced or unclear. It is straight forward to say "lighting-fixture in ceiling" but much less so to say "ceiling around lighting-fixture." Lack of clarity often results in ideas being defined incompletely. There are alternative ways of representing relationships explicitly in terms of relations and associated roles. These will be discussed in subsequent sections.

The AEC Model contains over twenty distinctly different relations. These relations tend to be more generic (i.e., less domain specific) than the concepts of the model. The relation "part" is an example of a relation that is clearly not limited to the building industry. In fact, the possibility that there exists a finite set of generic relations will be considered in later sections. Developing a particular model such as the AEC Model could therefore involve a process of selection from among generic relations, defining new domain specific relations only when necessary.

2.2 Relationship Types

The preliminary AEC Model uses an idea representation that employs the use of relationship pairs such as "has-part/part-of" in defining ideas. Four general types of relationships have been identified. The relationship types derive from certain grammatical constructions that can be used in the specification of ideas [8]. They include active, dative, locative, and partitive relationships. Obverse and inverse representations of example ideas using these relationship types are listed in Table 1.

Table 1. Example Ideas using Four Relationship Types.

Relationship Type	Obverse Representation	Inverse Representation
Active	*x controls y*	*y controll***ed-by** x
Dative	x *conducts***-***z***-to** *y*	*y receives-z-***from** *x*
Locative	*x on y*	*y under x*
Partitive	*x* **has-***part y*	*y part-***of** *x*

An **active relationship** uses a verb in the active and passive voice in its obverse and inverse representations respectively. The idea "hvac-system controls air-quality" is an example of an obverse representation. An active relationship is most easily identified by the inverse representation which uses the preposition "by" as in "air-quality controlled-by hvac-system." A listing of the active relations contained in the AEC Model is presented in Table 2. Active relations in this table are named by verbs only without reference to the use of the preposition "by" used to distinguish roles.

Table 2. Relations of the AEC Descriptive Model.			
Active	**Dative**	**Locative**	**Partitive**
accesses (5)* connects (8) contains (5) controls (1) defines (3) divides (5) generates (2) protects (1) serves (6) supports (2) triggers (1)	applies -finish (1) conducts -waste (7) -water (9) exhausts -air (3) leads -[person] (1)	in (2) on (2)	function (20) part (20) subset (485) subtype (485)
		* Numbers in parentheses indicate frequency of occurrance.	

A **dative relationship** is more complex than an active relationship. Dative relationships include a verb with the prepositions "to" and "from" in their obverse and inverse representations. An example of a dative relationship from the AEC Model is "gutter conducts-water-to down-spout." The AEC Model does not contain an inverse for this relationship though something like "down-spout receives-water-from gutter" might be chosen. Three concepts are identifiable (e.g., gutter, water, and down-spout) in an idea containing such a dative relationship. The idea typically involves the transfer of a thing from one object or place to another. Ideas involving transferrence (often discussed in the context of "directed networks") deserve special attention. The AEC Model chose to use a single binary representation for an idea involving a dative relationship in which the thing being transferred is included as part of the relationship. Alternatives to this approach will be discussed in subsequent sections. (See 3.2.2 and 3.3.)

Table 2 lists the dative relations of the AEC Model. There are five relationship pairs which identify dative relations. They include "applies-finish-to," "conducts-waste-to," "conducts-water-to," "exhausts-air-to," and "leads-[person]-to" (and their inverses). The prepositions "to" and "from" are not included in Table 2 since these prepositions serve to identify roles rather than the relation itself. Further, the verb and the object which constitutes the third concept in a dative relationship are separated. An advantage of listing dative relations in this way is that it identifies each of the elements explicitly. Within the AEC Model the relationship involving the application of a finish does not involve three concepts as does the generalized dative relationship. Rather it is expressed as "finish applied-to enclosure-component." A dative relationship using the generalized form would suggest an implied third concept, perhaps "[subcontractor] applies-finish-to enclosure-component." Similarly, there is an implied concept in the relationship "emergency-egress-route leads-[person]-to exit."

A **locative relationship** is identified by a preposition as in "lighting-fixture in ceiling."[1] The inverse representation of locative relationships are not always clear. Though technically speaking one might use "ceiling around lighting-fixture," this inverse relationship seems quite unnatural which may account for the fact that the AEC Model does not include an inverse for this relationship. Alternative means of specifying the roles played by concepts in a relationship can be employed to allay this difficulty. This is of particular interest since relations involved in locative relationships appear to be generic rather than domain specific lending them to standardization.

A **partitive relationship** is identified by the use of a noun in combination with the verb "has" in the obverse and by the preposition "of" in the inverse. "Building has-part building-element" and "building-element part-of building" are examples of a partitive relationship.[2] Moreover, the relationship pair "has-part/part-of" identifies a whole-to-part relationship that is a member of a subcategory of partitive relationships involving *generalization* [9]. Part-generalization can have implicit characteristics in knowledge-based information systems. For example, instances of a concept representing a whole can have instances of parts assigned automatically. This is a special kind of inheritance that can be very useful. Therefore, the appropriate use of part-generalization should be considered in the development of a conceptual schema.

Generalization can also be indicated by two other relationship pairs, "has-subset/subset-of" and "has-subtype/subtype-of."[3] The former pair identifies a set-generalization. Set-generalization does not involve inheritance of ideas. This derives from the fact that there are not inherent similarities among members of a set other than that they are each members of the same set. An example from the AEC Model is the concept of topography ("topography has-subset elevation," "topography has-subset orientation," and "topography has-subset slope"). In these ideas the concept "topography" is identified as comprising subsets of information on elevation, orientation, and slope. These subsets taken together constitute what is meant by topography. They do not inherit ideas from the concept topography which they serve to define.

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1 Locative relationships have an implied verb "is" as in "lighting fixture is-in ceiling."

2 The inverse representation of a partitive relationship has an implied "is" as in "building-element is-part-of building."

3 In many knowledge-based systems, the "has-subtype/subtype-of" relationship pair is discussed as the "is-a" relationship, where "subtype" is implied but not stated explicitly.

Type-generalization uses the third relationship pair used in generalizations ("has-subtype/subtype-of"). "Engineering-system has-subtype mechanical-system" and the inverse "mechanical-system subtype-of engineering-system" is an example. The use of these relationship pairs identifies a type-generalization which can be extended from one concept to another forming a type-generalization hierarchy. An important aspect of such use of type-generalization is the fact that many knowledge-based information systems use type-generalization for inheritance. That is, the concept mechanical-system would inherit ideas from the concept engineering-system.

The distinction between generalizations involving parts, subsets, and subtypes can be of major importance in developing conceptual schemas. This selection is often complicated, however, by the fact that the distinctions made here between part-, set-, and type-generalization are not universally observed by various modeling techniques. In the case of the AEC Model, the use of a particular modeling technique has resulted in some confusion among these choices.[1]

In addition to generalization, a second subcategory of partitive relationships involves what can be grouped together as *characterization*. This category includes all partitive relations that do not involve generalization. An example would be the relationship pair "has-function/function-of." As with the concepts themselves, relations used to characterize concepts can be either generic or domain specific in contrast to those involving generalization which include the three generic relations: part, subset, and subtype.

Table 2 lists the frequency of occurrence of the relations in the AEC Model. At the current phase of development most relationships involve generalization (i.e., the relations part, subset, and subtype). This reflects the development of the top level of organization for the conceptual schema and the descriptive function of the AEC Model.

It has also been observed that locative and partitive relations involving generalization tend to be generic (i.e., less domain specific). In contrast, the active and dative relations appear to be more specific to the building industry. Partitive relations involving characterization can be either generic or domain specific. Whether these tendencies will continue to be true as the AEC Model is developed and whether conceptual schemas in other domains display these same tendencies requires further attention. It represents an area of schema development and specification where various domains can contribute to one another's precision as well as holding potential for long term compatibility among domain specific systems through the development of conventions.

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1 The data model used by the IGES/PDES AEC committee in developing its "global model" is referred to as information analysis [10]. The notation used by information analysis provides a unique and simple representation for type-generalization. It does not, however, provide similar capabilities for part- and set- generalization.

3. Specifying Ideas

3.1 Alternative Representations

The field of conceptual modeling has in recent years had many alternative methods suggested for representing semantics in conceptual schemas [1]. Often these representations are part of a comprehensive approach to conceptual modeling called a data model (though it might be more useful to think of these data models as conceptual tools). The alternative representations have as their goal the expression of the underlying meaning of a conceptual schema. Three general ways of representing ideas are useful in discussing the AEC Model. They include symmetric, relational, and graphic representations.

3.1.1 Symmetric Representation

The most intuitive of the three representations is referred to here as a symmetric representation. The ideas of the AEC Model and the description of example ideas in Section 2 use a symmetric representation. Symmetric representations account for the fact that the concepts are often of central importance in understanding a conceptual schema. With this in mind, one defines relationship pairs that suggest the roles played by each of the concepts in an idea such that the idea can be viewed from the perspective of any given concept. In many information systems, the relationship pairs are defined as individual but associated "relations." They are associated in the sense that they are the inverse of one another. Therefore, when the idea "building has-part building-element" is established in such a conceptual schema, the inverse "building-element part-of building" should also be established.

Two types of difficulties are often present in developing a conceptual schema using a symmetric representation. The first is the uncertainty in assigning inverse roles. If we wish to establish "lighting-fixture in ceiling," is the inverse "ceiling around lighting-fixture?" The second difficulty involves semantic errors that stem from mixing relations. The classic example not taken from the building industry is the use of "x grandfather-of y" and "y grandson-of x." In addition to not taking into account granddaughters, the establishment of these relationships as being inverses of one another misses the fact that there are two relations employed with the following relationship pairs: "has-grandfather/grandfather-of" and "has-grandson/grandson-of." Developing a conceptual schema using a symmetric representation of relationships always has the potential for difficulties of the above kinds.

3.1.2 Relational Representation

An alternative to the symmetric representation of ideas is the use of a relational (or predicate logic) representation. The meaning contained within the relationship pairs of the symmetric representation is established through the use of compositional semantics (i.e., the position in an abstracted idea). The first element of the idea is the relation that describes the logical connection between concepts. The position of each subsequent concept within the idea indicates its role. In the above example, the relation "part" would be used to define an abstract idea involving appropriate roles such as "part (Whole, Part)."[1] Then for a given instance of the abstract idea, the role played by each concept is established by its position as in "part (building, building-element)."

A relational representation alleviates uncertainty that derives from the need to define relationship pairs required by a symmetric representation. However, since there is no standardization with regard to which position within an abstract idea will identify a given role, assignment is left to the developer and can vary from one system to the next. Even within a given system it is uncertain intuitively which role is associated with which position. Some degree of consensus on this topic would be most beneficial.

3.1.3 Graphic Representation

Another representation useful in specifying ideas employs a graphical notation such as that developed to represent the meaning contained in natural language called the conceptual graph [4]. A conceptual graph uses brackets to enclose concepts and parentheses to enclose relations between concepts. Directed arrows connote implicit roles of the concepts in the idea. The conceptual graph for a whole-to-part relationship between "building" and "building-element" is expressed as:

[building] → (part) → [building-element]

Using a relation in a conceptual graph suggests that it has previously been declared to be a relation associated with explicit roles. A formal derivation of a relation using conceptual graphs is beyond the scope of this report [4]. However, the above idea involving the part relation can be stated simply but explicitly using the following notation:

---

1 The language Prolog [11] uses this syntax which can be used to specify ideas in an information system. Alternatively, a relational representation can be expressed as a simple list of elements as in "[part, Whole, Part]."

(part) -

{Whole} - [building]
{Part} - [building-element]

This can be generalized to the following abstract representation of an idea:

(Relation) -

{Role} - [Concept]
{Role} - [Concept]
. . .

3.2 Defining and Using Relationship Types

In reviewing the AEC Model, it was observed that many of the ideas were similar in terms of the relationships used. Four relationship types were sufficient for grouping all relationships. The relationship types used for this purpose were Active, Dative, Locative, and Partitive. These names were chosen to reflect natural language constructions that can be used in expressing relationship pairs in a symmetric representation of ideas. The notation introduced in the previous section can be used to define the four relationship types with explicit roles which hold for all relationships that are of that type.

3.2.1 Active Relationships

Active relationships are defined using an active relation (ActRel) and roles identifying an actor (Actor) and an acted upon object (ActObj) as follows (the relationship appears in bold face in this and subsequent definitions of relationship types):

(ActRel) -

{Actor} - [Concept]
{ActObj} - [Concept]

Specifying an idea that uses an active relationship therefore requires identifying the ActRel and the Concepts in accordance with this type definition.

(controls) -

{Actor} - [hvac-system]
{ActObj} - [air-quality]

Active relationships therefore are seen as comprising an active relation and two concepts that fulfill the roles of Actor and ActObj. Since the specification of such a relationship serves to declare the existence of a given active relation, it can thereafter be represented in an implicit representation as:

[hvac-system] → (controls) → [air-quality]

This is the format that was first introduced for an implicit graphic representation of an idea, but has been derived in a way that removes ambiguity as to the roles played by each concept in the idea. Establishing the roles which are a part of the graph makes the meaning explicit. Table 3 lists the ideas which involve active relationships in the AEC Model in terms of an ActRel, an Actor, and an ActObj.

Once defined in this fashion, specifying a relational representation for ideas using active relationships can be stated in terms of the following abstraction and example:

ActRel (Actor, ActObj)
controls (hvac-system, air-quality)

If there is consensus on the order in which the roles are listed for the abstracted idea, a source of confusion is avoided in specifying all further ideas that use this relationship type.

3.2.2 Dative Relationships

Dative relationships have been defined using a dative relation (DatRel) and roles identifying a dative object (DatObj), a source (Source), and a target object (Target) as follows:

(DatRel) -
{DatObj} - [Concept]
{Source} - [Concept]
{Target} - [Concept]

Specifying an idea that uses a dative relationship therefore requires identifying the DatRel and the Concepts playing the roles of DatObj, Source, and Target.

(conducts) -
{DatObj} - [water]
{Source } - [gutter]
{Target} - [down-spout]

Table 3. Ideas Using Active Relationships of the AEC Model.

ActRel	Actor	ActObj
accesses	artificial-light-system	electrical-system
	engineering-system	utility-system
	natural-light-sytem	opening
connects	air-distribution-network	hvac-distribution-device
	electric-circuit-network	electrical-component
	footing-drain	cleanout
	stack	vent
	water-distribution-network	water-fixture
	water-distribution-network	hvac-distribution-device
	water-distribution-network	standpipe-component
	water-distribution-network	sprinkler-component
contains	circulation-system	emergency-egress-route
	emergency-egress-route	room
	enclosure-component	opening
	occupied-room	furniture
	space	equipment
controls	hvac-system	air-quality
defines	enclosure-system	room
	external-envelope	exterior
	internal-subdivision	interior
divides	electric-zone	electrical-system
	hvac-zone	hvac-system
	lighting-zone	lighting-system
	sprinkler-zone	sprinkler-system
	standpipe-zone	standpipe-system

(continued)

Table 3. (continued)		
ActRel	**Actor**	**ActObj**
generates	luminaire	heat
	luminaire	noise
protects	over-current-device	electric-circuit-network
serves	street-main	meter
	meter	service-equipment
	service-equipment	feeder
	feeder	branch-circuit
	branch-circuit	junction-box
	junction-box	electric-equipment-network
supports	structural-system	building-system-component
	raceway	electric-circuit-network
triggers	control	instrument

An idea involving a dative relationship therefore is seen as comprising a dative relation and three concepts that fulfill the roles of DatObj, Source, and Target. Table 4 lists the ideas that involve dative relationships in the AEC Model in terms of these components.

An implicit representation of a dative relationship is problematic in that it is not a binary relationship. Dative relationships can be viewed as a binary relationship in which the DatRel and DatObj are combined to form a unique relation. The AEC Model expresses dative relationships in this fashion. The implicit representation of an idea involving a dative relationship resulting from the combination of the DatRel and the DatObj is as follows:

[gutter] → (conducts-water) → [down-spout]

Table 4. Ideas Using Dative Relationships of the AEC Model.		
DatRel -DatObj	**Source**	**Target**
applies		
-finish	[subcontractor]	enclosure-component
conducts		
-waste	branch-soil-pipe	stack
	building-drain	bulding-trap
	building-sewer	main-sewer
	building-trap	building-sewer
	fixture-trap	branch-soil-pipe
	fresh-air-fixture	fixture-trap
	stack	building-drain
-water	down-spout	discharge-component
	footing-drain	sand-interceptor
	gutter	down-spout
	gutter	roof-drain
	large-paved-area	discharge-component
	roof	gutter
	roof-drain	discharge-component
	sand-interceptor	discharge-component
	steep-slope	discharge-component
exhausts		
-air	branch-vent	vent
	fresh-water-fixture	branch-vent
	vent	vent-stack-terminal
leads		
[-person]	emergency-egress-route	exit

A relational representation for such an idea involving a binary dative relationship can be stated in terms of the following abstraction and example:

DatRel-DatObj (Source, Target)
conducts-water (gutter, down-spout)

The alternative to the above combination of the DatRel and the DatObj is a representation which accommodates a tertiary relationship.

DatRel (DatObj, Source, Target)
conducts (water, gutter, down-spout)

The latter representation of an idea involving a tertiary dative relationship is preferred to the form which combines the dative relation and object. (See Section 3.3 for a further discussion of this topic.)

3.2.3 Locative Relationships

Locative relationships have been defined using a locative relation (LocRel) and roles which identify a located object (LocObj) and a location (Location) as follows:

(LocRel) -
    {**LocObj**} - [Concept]
    {**Location**}- [Concept]

Specifying an idea that uses a locative relationship requires identifying appropriate components in accordance with the type definition.

(in) -
    {LocObj} - [lighting-fixture]
    {Location}- [ceiling]

Ideas which involve locative relationships are seen as comprising a locative relation and two concepts that fulfill the roles of LocObj and Location. Table 5 lists the ideas involving locative relationships of the AEC Model in terms of a LocRel, a LocObj, and a Location.

Table 5. Locative Relationships of the AEC Model.		
LocRel	**LocObj**	**Location**
in	lighting-fixture outside-siamese-connector sprinkler-head	ceiling exterior-wall ceiling
on	building roof-manifold	site roof

An implicit representation of the above example idea using a locative relationship is:

[lighting-fixture] → (in) → [ceiling]

A relational representation for ideas using a locative relationship can be stated in terms of the following abstraction and example:

LocRel (LocObj, Location)
in (lighting-fixture, ceiling)

Though most locative relationships are binary there exists the possibility of tertiary or higher order locative relationships. The relation "between" requires the ability to deal with higher order relationships. A locative relationship involving the relation between would necessarily have at least two (and possibly more) concepts with the Location role. Since the roles of each of these concepts is the same, additional locations can be accommodated by repeating that role.

3.2.4 Partitive Relationships

Partitive relationships have been defined using a partitive relation (ParRel) and roles indicating a primary object (PrimObj) and an auxiliary object (AuxObj) as follows:

```
( ParRel ) -
     {PrimObj}      - [ Concept ]
     {AuxObj}       - [ Concept  ]
```

The roles PrimObj and AuxObj have been chosen so they can be applied to both subcategories of partitive relationships (i.e., both generalization and characterization). Specifying an idea using a partitive relationship requires identifying each of the components:

(subtype) -
{PrimObj} - [engineering-system]
{AuxObj} - [mechanical-system]

An idea involving a partitive relationship therefore has a partitive relation and two concepts that fulfill the roles of PrimObj and AuxObj. An implicit representation of the above idea is:

[engineering-system] → (subtype) → [mechanical-system]

A relational representation for an idea using a partitive relationship can be stated in terms of the following abstraction and example:

ParRel (PrimObj, AuxObj)

subtype (engineering-system, mechanical-system)

Most ideas in the AEC Model involve partitive relationships. A table of the ideas that employ partitive relationships in terms of ParRel, PrimObj, and AuxObj is not included in this report. Most of the partitive relations of the AEC Model (see Table 2) involve generalization but do not consider the distinctions suggested previously. In those cases where inheritance is judged to be relevant, the distinction between part- and type-generalization should be considered. In those that do not involve inheritance, set-generalization is appropriate. This topic will be discussed in terms of specific examples used to organize information within the conceptual schema in Section 4.2.

3.3 Complex Ideas

Ideas involving dative relationships contain a dative relation and three concepts (an arity of three when considered from the perspective of a relational representation). Such ideas while easily represented in a relational form are not represented accurately by a single symmetric binary idea. Therefore, an alternative representation is desirable. A complex idea requires a representation which employs more than one binary idea to convey the required semantics.

3.3.1 Representing Complex Ideas

An idea involving a dative relationship contains a dative relation (DatRel) and three concepts having the roles of a dative object (DatObj), a source (Source), and a target (Target) as in the following example (not from the AEC Model):

```
(ships) -
        {DatObj}  - [ material ]
        {Source}  - [ supplier ]
        {Target}  - [ contractor ]
```

Such a tertiary idea can be represented in a binary format using one binary idea involving an active relationship and two binary ideas involving partitive relationships. An additional concept is used that identifies an implied process of transfer (e.g., "supplier-to-contractor-material-transfer").

```
(ships) -
      {Actor}   -[ supplier-to-contractor-material-transfer ]
      {ActObj}  -[ material ]
(origin) -
      {PrimObj} -[ supplier-to-contractor-material-transfer ]
      {AuxObj}  -[ supplier ]
(destination) -
      {PrimObj} -[ supplier-to-contractor-material-transfer ]
      {AuxObj}  -[ contractor ]
```

The corresponding implicit representations are as follows:

[supplier-to-contractor-material-transfer] → (ships) → [material]
[supplier-to-contractor-material-transfer] → (origin) → [supplier]
[supplier-to-contractor-material-transfer] → (destination) → [contractor]

The relational representations for these ideas are:

ships (supplier-to-contractor-material-transfer, material)
origin (supplier-to-contractor-material-transfer, supplier)
destination (supplier-to-contractor-material-transfer, contractor)

The relationship pairs of a symmetric representation are "ships/shipped-by," "has-origin/origin-of," and "has-destination/destination-of" respectively.

3.3.2 The Utility of Complex Ideas

An underlying concept of transfer appears central to the representation of complex ideas involving dative relationships as currently defined. Semantic information is appropriately maintained within a binary format by establishing a complex idea centered around this additional concept.

While using an idea involving an active relationship in representing a complex idea falls within the scope of previous discussions, combining such an idea with paired ideas involving partitive relationships to express direction adds another aspect to the representation of ideas. Such pairing of ideas has been identified in the field of natural language processing by Schank [8]. In addition to the expression of direction (from source to target) is that of state change (from initial to final states). Both direction and state change fit well within the context of the transfer process as being central to complex ideas involving dative relationships.

Certainly the idea of directed transfer is useful to the building industry especially in the context of "directed networks." Many building systems can be viewed as a collection of connected and ordered components that transfer a given thing for the purpose of satisfying explicit functional requirements. The potential of the complex idea mechanism representing not only directed transfer but also state change will continue to be an active topic of research.

4. From Initial Concepts to Constructs

4.1 Developing Concepts

Initial concepts are chosen by individuals who understand the needs of the given domain for which a conceptual schema is being developed. Therefore, it is the participants involved in the design, construction, and maintenance of a building throughout its entire life cycle that ultimately determine the concepts that must be represented in a global model. The preliminary AEC Model used as a basis of discussion in this report is a first step toward identifying a comprehensive set of concepts for the building industry.

Once a concept such as building is identified, it can be represented using the conceptual graph form [building]. This form represents the initial concept. The next step is to begin to develop the concept by specifying ideas in which the concept is logically connected to other concepts, such as:

[building] → (part) → [building-element]

An idea can also be expressed in the following form:

(part)
    ←[building]
    →[building-element]

This representation can be further abbreviated by assuming that the first concept points toward the relation and the second points away from it as follows:

(part)
    [building]
    [building-element]

The form can then be used in a shorthand version which includes similar ideas involving the same relation and initial concept by adding the concepts to which the initial concept is related from those other ideas.

(part)
    [building]
    [building-element]
    [building-system]

What is understood to constitute the concept of a building at later stages of concept development includes all those ideas in which the concept is directly involved (i.e., an aggregation of ideas [9]). The developed concept of a building in the AEC Model can be represented as:

```
(part)
    [building-project]
    [building],
(part)
    [building]
    [building-element]
    [building-system],
(on)
    [building]
    [site],
(function)
    [building]
    [building-function].
```

4.2 Identifying Constructs

Constructs are hierarchical conceptual structures formed by a synthesis of ideas that involve generalization. In the case of part-generalization, for example, a given concept is understood to be made of a number of parts which in turn are made of parts and so on forming a hieararchy of parts. The originating concept, in this case, represents a composite construct. The use of part-, set-, or type-generalization with the originating concept identifies a construct as being a composite, set, or classification respecitively.

4.2.1 Composites

Composites are constructs that serve to identify a whole as being made of a number of parts. Composites therefore use part-generalization at the originating level of the construct. An example composite for a building might view it as a simple list of parts (an approach not taken by the AEC Model).

```
(part)
    [building ]
    [ceiling]
    [floor]
    . . .
```

In the above example any or all of the parts could themselves be made of parts and the composite construct of a building would include the ideas representing that further breakdown.

An alternative composite views a building as including only the concepts building-system and building-element at the originating level. Building-system and building-element are in turn made up of various kinds of systems and elements. This is the approach used in the AEC Model.

```
(part)
        [building]
        [building-element]
        [building-system],
(subtype)
        [building-element]
        [ceiling]
        [floor]
        [roof]
        [room]
        [wall],
(subtype)
        [building-system]
        [engineering-system]
        [non-engineering-system],
...
```

Since in this construct a wall is a subtype of a building element, and a building element is a part of a building, it follows that a wall is also a part of a building. Similarly parts or subtypes of a wall can also be seen to be included in a composite view of a building. This example illustrates the use of a concept classification (involving type-generalization) being incorporated within a composite construct.

4.2.2 Sets

Sets are constructs that use set-generalization at the originating level. Sets identify collections of concepts that do not necessarily have anything in common other than that they are members of the same set.

4.2.3 Classifications

Classifications are constructs that provide the ability to view information in a hierarchical arrangement of categories, each subsequent level adding more detailed information. Classifications use type-generalization at the originating and all subsequent levels of the construct. They are often included as a portion of composite constructs (see Section 4.2.1). Classifications are particularly useful in organizing building information where taxonomies of building elements and systems are central issues in developing a global model.

An important aspect of the AEC Model is its systems approach to organizing information about a building. Figure 1 presents a hierarchy that represents the classification of concepts under the heading of building-system. The representation is of the structure only and does not explicitly identify the relationships between concepts involving type-generalization. However, since the structure is identified as a classification, the subtype relation is implied throughout.

An alternative classification is presented in Figure 2. This classification takes the view that building systems can be subdivided into enclosure, interior, mechanical, and structural systems. All other building systems fall under these four classes. This alternative structure reflects an organization suggested in "The Building Systems Integration Handbook" published by the American Institute of Architects [12]. Deciding between such details within a generalization hierarchy is a major aspect of developing a conceptual schema.

Table 6. presents the ideas of the building-system classification shown in Figure 2.

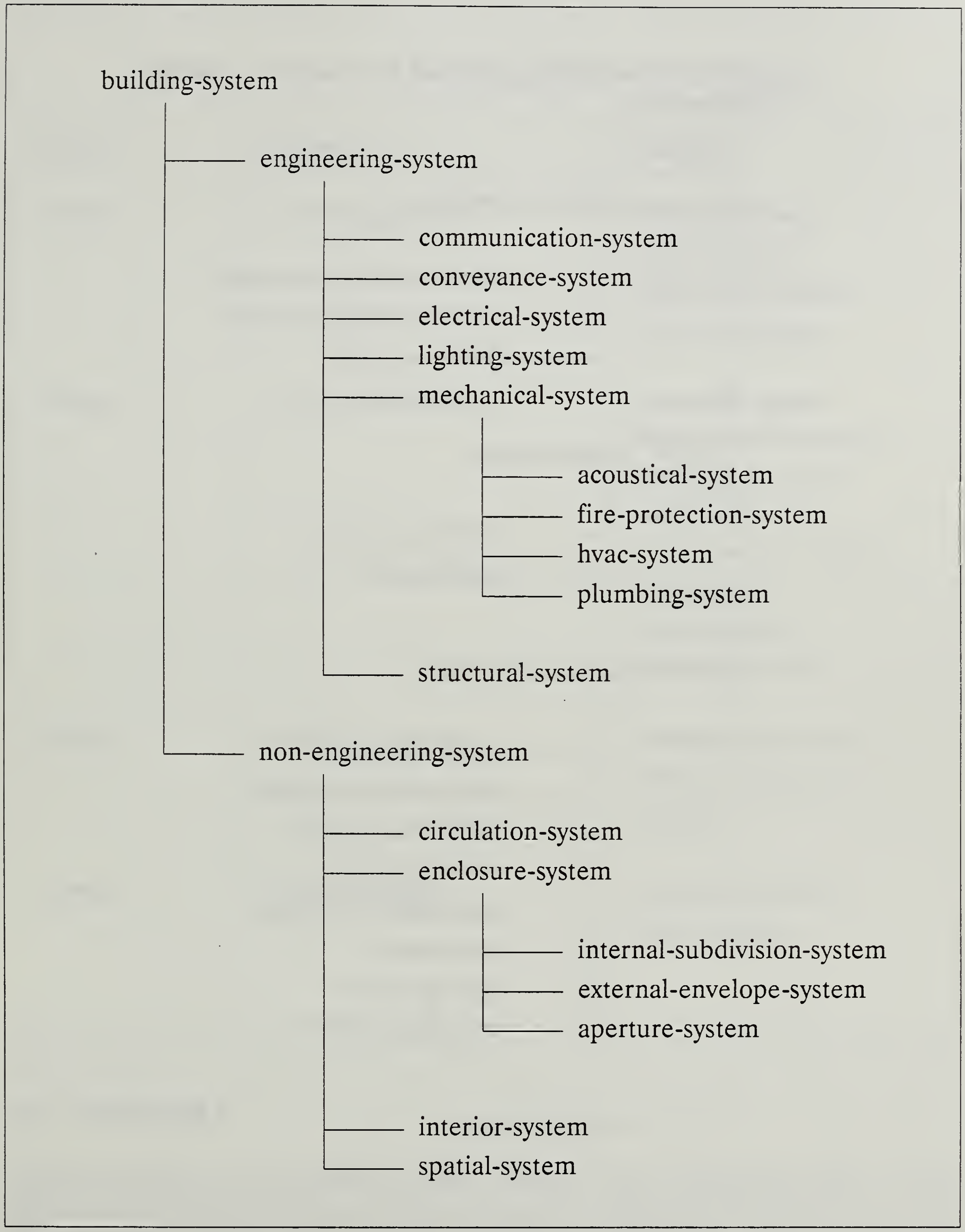

Figure 1. A Building-System Classification.

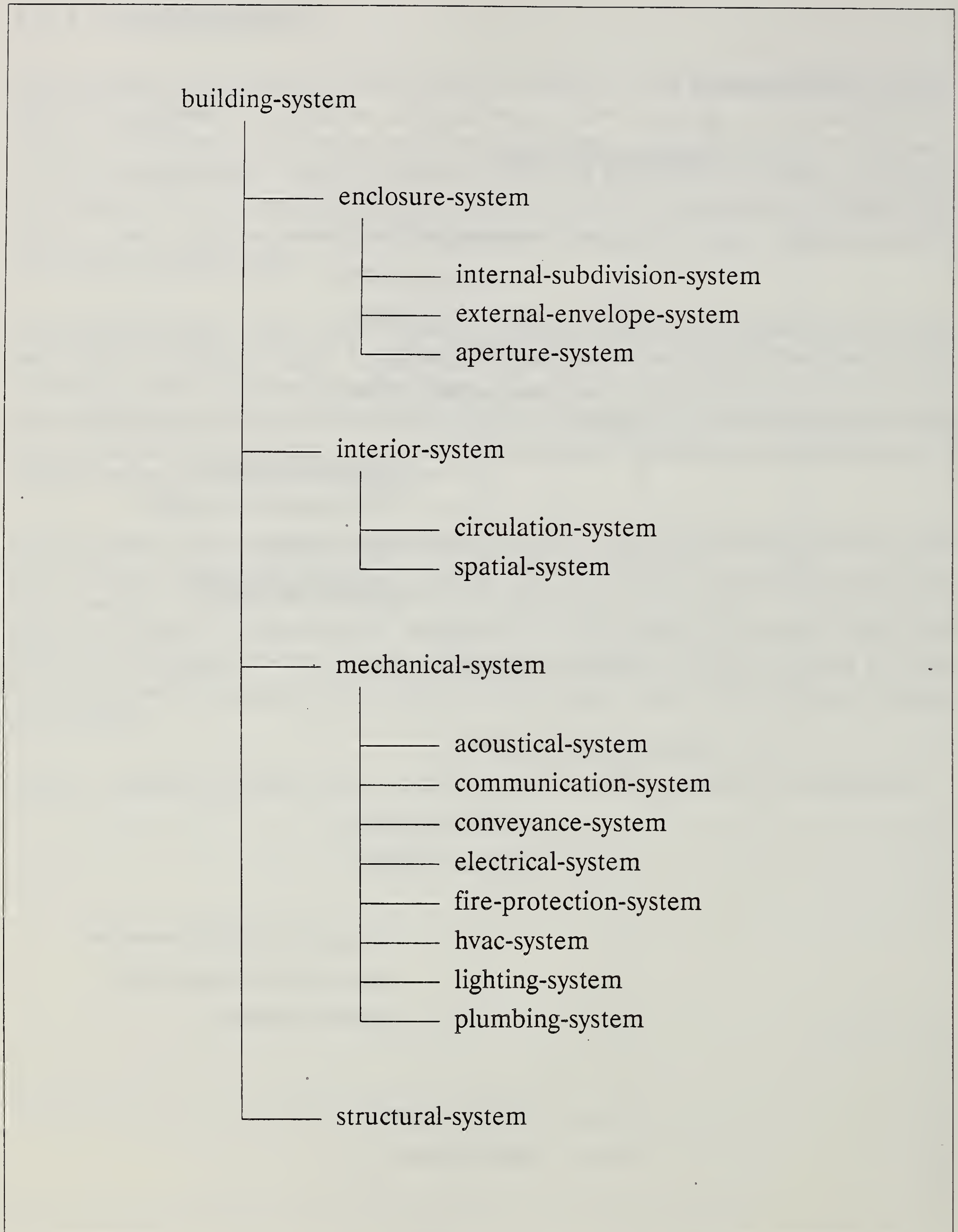

Figure 2. An Alternative Building-System Classification.

Table 6. Ideas in a Building-System Classification.		
ParRel	**PrimObj**	**AuxObj**
subtype	building-system	enclosure-system interior-system mechanical-system structural-system
subtype	mechanical-system	acoustical-system communication-system conveyance-system electrical-system fire-protection-system hvac-system lighting-system plumbing-system
subtype	enclosure-system	internal-subdivision external-envelope opening
subtype	interior-system	circulation-system spatial-system

4.3 Prototypes

When a concept is developed and that concept is also contained within a type-generalization hierarchy, the developed concept (i.e., its ideas) can be inherited within the context of that hierarchy. This kind of construct is referred to here as a prototype concept. It is something of a cross between a developed concept and a construct. It includes both the aggregation of ideas in which the initial concept is involved and possibly other selected ideas that extend beyond that aggregation.

Table 7. Ideas in a Prototype Engineering-System.

Relation	Concept 1	Concept 2
accesses	engineering-system	utility-system
divides	zone	engineering-system
part	engineering-system	system-component
part	engineering-system	directed-network
part	directed-network	device-part
represents	device-part-geometry	device-part
supports	structural-system	system-component
triggers	control	instrument
subtype	system-component	control device-part instrument insulation

Within its building-system classification, the AEC Model has developed a prototype engineering-system (Figure 7). This prototype serves as a template for developing the concepts of mechanical and structural systems since it specifies ideas that are believed to hold for all types of engineering systems.

In considering what constitutes an hvac-system, the prototype engineering-system can be inherited if the hvac-system is related to a mechanical-system which in turn is related to an engineering-system by type-generalization. Therefore, the development of the hvac-system concept begins with inherited ideas which can be derived from the prototype engineering-system followed by ideas that uniquely specify the hvac-system concept.

Table 8. Inherited Ideas of an HVAC-System Concept.		
Relation	**Concept 1**	**Concept 2**
accesses	hvac-system	utility-system
divides	zone	hvac-system
part	hvac-system	system-component
part	hvac-system	directed-network
part	directed-network	device-part
represents	device-part-geometry	device-part
supports	structural-system	system-component
triggers	control	instrument
subtype	system-component	control device instrument insulation

In fact, it is this addition of lower level specific ideas to higher level general ideas that justifies the use of type-generalization. If unique information is not added by lower level classes, the division into subtypes is probably not appropriate.

Table 8 presents the inherited ideas that serve to develop the concept of an hvac-system. Table 9 expands upon the concept by adding ideas that are unique to an hvac-system. Such inheritance, from a prototype to concepts that represent subtypes of the prototype, is a capability that needs to be considered when developing generalization hierarchies.

Table 9. Non-Inherited Ideas of an HVAC-System Concept.		
Relation	**Concept 1**	**Concept 2**
connects	air-distribution-network	air-distribution-device
conntects	water-distribution-network	water-distribution-device
subtype	control	temperature-control air-flow-control
subtype	device-part	air-terminal conditioner-device air-distribution-device water-distribution-device water-terminal
subtype	air-terminal	air-distribution-ceiling diffuser door grille light-fixture louver register roof-ventilator screen skylight vent window
subtype	conditioner-device	cooling-conditioner heat-conditioner humindity-conditioner

(continued)

Table 9. (continued)		
Relation	**Concept 1**	**Concept 2**
subtype	water-terminal	convector radiant-panel radiator unit-heater

5. Summary and Conclusions:

5.1 The Conceptual Schema Development Process

The development of a conceptual schema such as the AEC Model has at least four essential aspects. They include:

Topic	Process
Concepts	identification and development
Relationships	selection of Relation &Roles
Ideas	assignment of Roles to Concepts
Constructs	identification and development

The process of schema development begins with the identification of concepts appropriate to a given domain. In the case of the building industry, this is itself a formidable task and is therefore expected to be a continuing effort.

In contrast to the large number of concepts that can be expected in a global conceptual model, the number of relations used in describing relationships between concepts is much smaller. Further, many relations that are appropriate for the building industry are also useful in other domains. Therefore, identifying relations should be a matter of selection from among previously identified relations. This aspect of schema development lends itself to cooperative efforts across disciplines.

A problem that is encountered, however, is that there is little or no standardization in the manner in which relationships are specified. Many data models (in the sense of tools used to develop schemas) have their own way of defining relationships. Whether the relation and roles remain separate or are combined in a single representation is the most obvious difference. However, the details of the words used to express the relationships and the precise syntax of their specification continues to be problematic. This report has described an initial step toward resolving this important issue.

The lack of consensus is also serious in the case of specifying ideas. Many alternative representations exist. This report has described three general kinds of representation as an overview of the sorts of differences that exist. However, it is important to note that they should be truly alternative representations. The underlying semantics must remain the same though expressed in different ways. In those cases where a particular representation cannot accommodate necessary semantics, extensions to the representation are justified.

What has not been a part of the specification of ideas in the past is the use of relationship types to assist the schema developer. Ideas when specified in a form close to natural language (e.g., a symmetric representation) should use certain grammatical constructions. The definition of active, dative, locative, and partitive relationship types makes this point explicit. Roles have then been established that reflect the underlying semantics attached to concepts involved in these types of relationships. This approach allows for explicit statements of meaning that can serve as a check for alternative representations. In this context, a representation for complex ideas has been developed for the special case of ideas involving dative relationships to address the underlying semantics of directed transfer.

Another aspect of developing a conceptual model emphasized in this report is the importance of identifying and developing constructs within the conceptual schema. Composites, sets, and classifications serve to establish hierarchically related groups of ideas within a conceptual schema. Identifying constructs involves important choices that must be made between part-, set-, and type-generalization. When using type-generalization, the specification of prototypes can serve as templates in developing lower level concepts within a classification.

These aspects of the development of conceptual models need further review and research. They can, however, be applied to ongoing schema development as an aid to the developer in considering the many choices that are to be made during that process.

5.2 Natural Expression of Ideas

The development of a conceptual schema using representations that are similar to natural language expressions benefits both the developer and most other individuals that are to make use of the schema. Internal computer representations vary greatly from one implementation to another. Clear conceptual representations offer a means by which systems can be developed that are capable of communication both within and between disciplines.

This report has presented a view of how ideas and other conceptual structures can be specified unambiguously. Adoption of such an approach (see Table 10 as an example) presents the possibility for more direct comparison and integration of conceptual schemas than is currently the case. Particularly in the realm of relationships, the potential for developing a consensus semantic vocabulary from which schema developers and integrators can choose seems of considerable relevance to standardization organizations.

Table 10. Natural Expression of Ideas by Relationship Type.		
Active		
Idea:	ActObj_ActRel[1]	air-quality_control
Obv:	Actor ActRel[s][2] ActObj	hvac-system controls air-quality
Inv:	ActObj [is-]ActRel[ed-by][3] Actor	air-quality is-controlled-by hvac-system
Dative *(Complex Idea)*		
Idea:	Source_[to]_Target_DatObj_[transfer[4]]	gutter_to_downspout_water_transfer
Obv:	Source-[to]-Target-DatObj-[transfer]	gutter-to-downspout-water-transfer
	" DatRel[s] DatObj	" conducts water
	" [has-origin] Source	" has-origin gutter
	" [has-destination] Target	" has-destination downspout
Inv:	Source-[to]-Target-DatObj-[transfer]	gutter-to-downspout-water-transfer
	DatObj [is-]DatRel[ed-by] "	water is-conducted-by "
	Source [is-origin-of] "	gutter is-origin-of "
	Target [is-destination-of] "	downspout is-destination-of "
Locative		
Idea:	LocObj_[location]	building_location
Obv:	LocObj [is-]ObvLocRel Loc	building is-on site
Inv:	Loc [is-]InvLocRel LocObj	site is-under building
Partitive		
Idea:	PrimObj_ParRel	building_part
Obv:	PrimObj [has-]ParRel AuxObj	building has-part building-element
Inv:	AuxObj [is-]ParRel[-of] PrimObj	building-element is-part-of building

1 Beginning capital letters indicate variables.
2 Letters, words, and characters in brackets are used literally.
3 Normal rules of English grammar apply.
4 Complex ideas involving dative relationships represent directed transfer.

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The development of a global model for building-project information requires a precise description of the meaning of the information to be maintained. This report presents an analysis of the conceptual structures that are available to specify that meaning using an "as-designed" global model as an example. This model is currently under development by the Architecture, Engineering, and Construction (AEC) Committee of the Initial Graphics Exchanges Specification (IGES)/Product Data Exchange Specification (PDES) Organization.

The key conclusion of this analysis is that a core semantic vocabulary is needed. This core vocabulary derives from how meaning is expressed without regard for specific domains of information. Preliminary elements of such a core vocabulary are defined. Further, a means by which that core is extended to add necessary domain-specific semantics is presented. The analysis has identified those aspects of developing a global model for building-project information that should proceed in the context of a broad interdisciplinary effort to represent information and those that require extensive technical input from the building industry.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

building data; building information; conceptual modeling; data modeling; information modeling; semantic modeling

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